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FINAL TECHNICAL REPORT
COLLECTION AND ASSESSMENT
OF AIRCRAFT EMISSIONS BASE-LINE DATA
TURBOPROP ENGINES
(Allison T56-A-15)

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Detroit Diesel Allison Division • General Motors
Indianapolis, Indiana

EDR 7200
September 1971

Environmental Protection Agency
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Ann Arbor, Michigan

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Experimental data were analyzed by converting the concentration values measured for each engine to mass emissions over a landing and takeoff (LTO) cycle representative of a commercial flight with T56-type engines and then performing a statistical analysis to obtain mean and standard deviation values.

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Details of illustrations in
this document may be better
studied on microfiche

FOREWORD

This report describes the work performed by Detroit Diesel Allison, Division of General Motors, Indianapolis, Indiana, for the Environmental Protection Agency (EPA), Office of Air Programs, Ann Arbor, Michigan, under EPA Contract No. 68-04-0029 during the period 1 June through 16 August 1971. Mr. C. L. Gray was the Project Officer for EPA and Mr. E. S. McLean was the Contracting Officer for EPA.

Detroit Diesel Allison has assigned Report Number EDR 7200 to this publication which was submitted in August 1971.

Publication of this report does not constitute Environmental Protection Agency approval of the report's findings or conclusions.

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I. INTRODUCTION

Public Law 91-604, "Clean Air Amendments of 1970," requires establishment of exhaust emission standards for aircraft by the end of 1971. Detroit Diesel Allison, under contract to the Environmental Protection Agency, accomplished a program with the objective of collecting and assessing base-line exhaust emission data on Allison T56-A-15 turboprop engines.

During the contract period of performance, computerized data handling and statistical analysis programs were developed, exhaust emissions of eleven production T56-A-15 engines were measured, and a landing-takeoff (LTO) emission test cycle was developed.

This report, which covers the contract effort and describes in detail such items as measurement systems, test program, data analysis, and computation methods, contains five major sections with primary emphasis on three: Experimental, Analysis, and Conclusions and Recommendations. It is presented to promote industry-wide information exchange and aid in establishment of aircraft emissions standards and measurement techniques.

II. SUMMARY

Exhaust emissions data were collected and evaluated from eleven new T56-A-15 military turboprop engines during their production-line performance evaluation. The normal production test schedule was used. The following measurements were made:

- CO, CO_2, and NO—Luft-type Infrared Analyzers (LIRA)
- Hydrocarbons—Heated Flame Ionization Detector (FID)
- Smoke—SAE smokemeter
- NO and NO_2—Chemiluminescent analyzer
- NO plus NO_2—Modified Saltzman method
- Oxygenated compounds—MBTH method

Fuel drainage was also measured. Particulate data according to the LACAPCD method were furnished from other experiments.

Experimental data were analyzed by converting the concentration values measured for each engine to mass emissions over a landing and takeoff (LTO) cycle representative of a commercial flight with T56-type engines and then performing a statistical analysis to obtain mean and standard deviation values.

Emission measurements were satisfactory; the average emission levels and variations were determined over the operating range of each engine. However, the variations could not be specifically proportioned between true engine variation, instrument variability, and that incurred by measuring a production test cycle and converting to the emissions cycle. It is recommended that true engine variability and instrument variability be assessed by a test which includes a large number of engines (samples) and a statistically planned evaluation of instrument error.

The LTO emission test cycle used for the analysis was developed from a study of Model T56 engine-powered aircraft. It showed that LTO total mass emissions were highly sensitive to the length of time that the aircraft was held stationary during ground operations. Because of the degree of its influence on total mass emissions, aircraft handling and all of its variabilities should be divorced from engine emissions test cycles.

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III. EXPERIMENTAL

This section describes the testing, the methods and equipment used, and the data directly obtained. Comments on the experimental work are also included.

ENGINE DESCRIPTION

The engine selected for exhaust emissions evaluation was the Allison T56-A-15 turboprop engine. This model is one in a series of military T56 engines; the Allison Model 501 is their commercial counterpart. All engines in these series consist of an internal combustion gas turbine power section, connected by extension shafting and a supporting structure to a single reduction gear assembly which has a single propeller shaft. In the T56-A-15, this shaft is offset above the power section center line. The power section contains six combustion chambers of the through-flow type assembled within a single annular chamber and incorporates a fourteen-stage axial-flow compressor directly coupled to a four-stage air-cooled turbine (Figure 3-1).

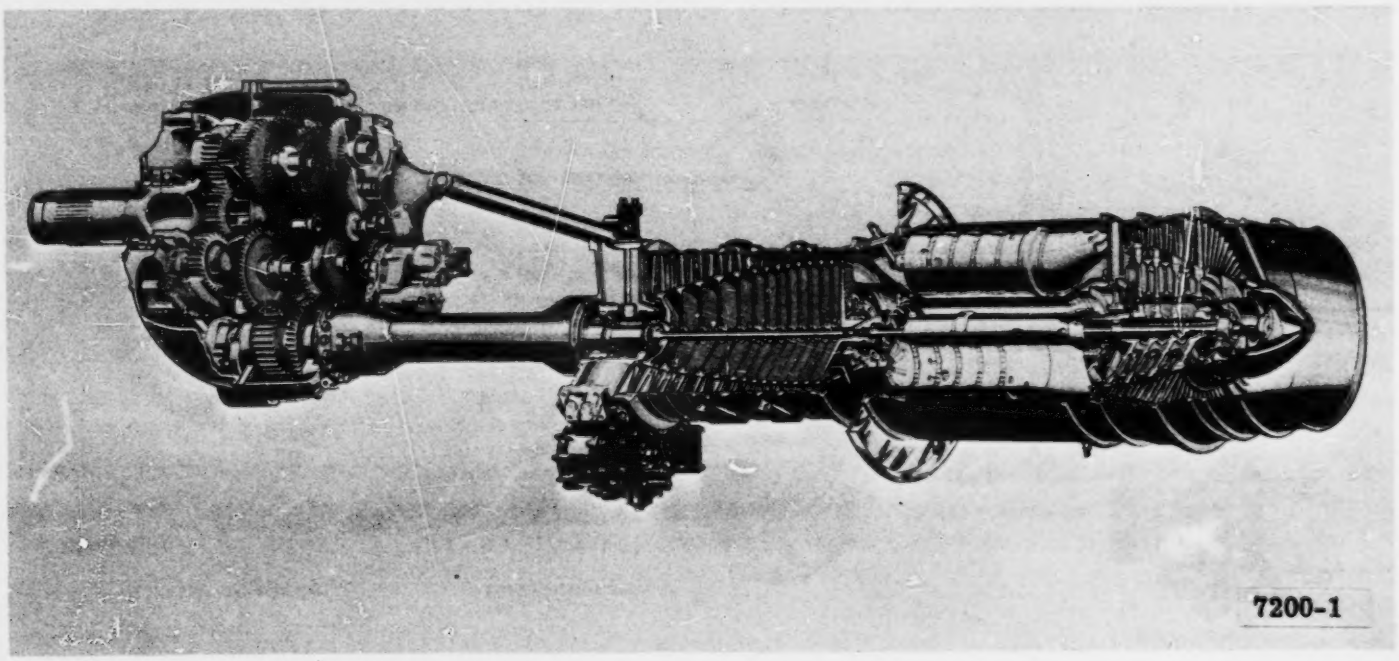

Figure 3-1. T56-A-15 engine cutaway.

General Operation

During operation, air enters the power section through the air inlet housing (Figure 3-2) and is compressed by the compressor. The compressed air flows through the diffuser into the combustion liners where fuel is introduced and the fuel-air mixture is ignited, after which it burns continuously. The resultant gases exit through the aft ends of the combustion liners and flow through the turbine where the energy of the gas is extracted and converted into usable kinetic energy to drive the compressor and reduction gear. The gases exiting the turbine have some residual energy which creates a small amount of jet thrust. The power supplied to the reduction gear by the power turbine is converted from high rpm-low torque energy to the lower speeds and subsequent higher torque required for efficient propeller operation.

Engine operation is controlled by coordinated operation of the fuel, electrical, and propeller control systems. A characteristic of this turboprop engine is that changes in power are not related to engine speed but, rather, to turbine inlet temperature. During flight, the propeller maintains a constant engine speed, which is 100% rated speed of the engine and is the design speed at which most power and best overall efficiency can be obtained. Therefore, fuel flow is changed to affect power requirements. An increase in fuel flow results in a higher turbine inlet temperature and a corresponding increase in available energy at the turbine. The turbine then absorbs more energy and transmits it to the propeller in the form of torque. The propeller, in order to absorb the increased torque, increases blade angle and, in the process, maintains constant engine rotational speed.

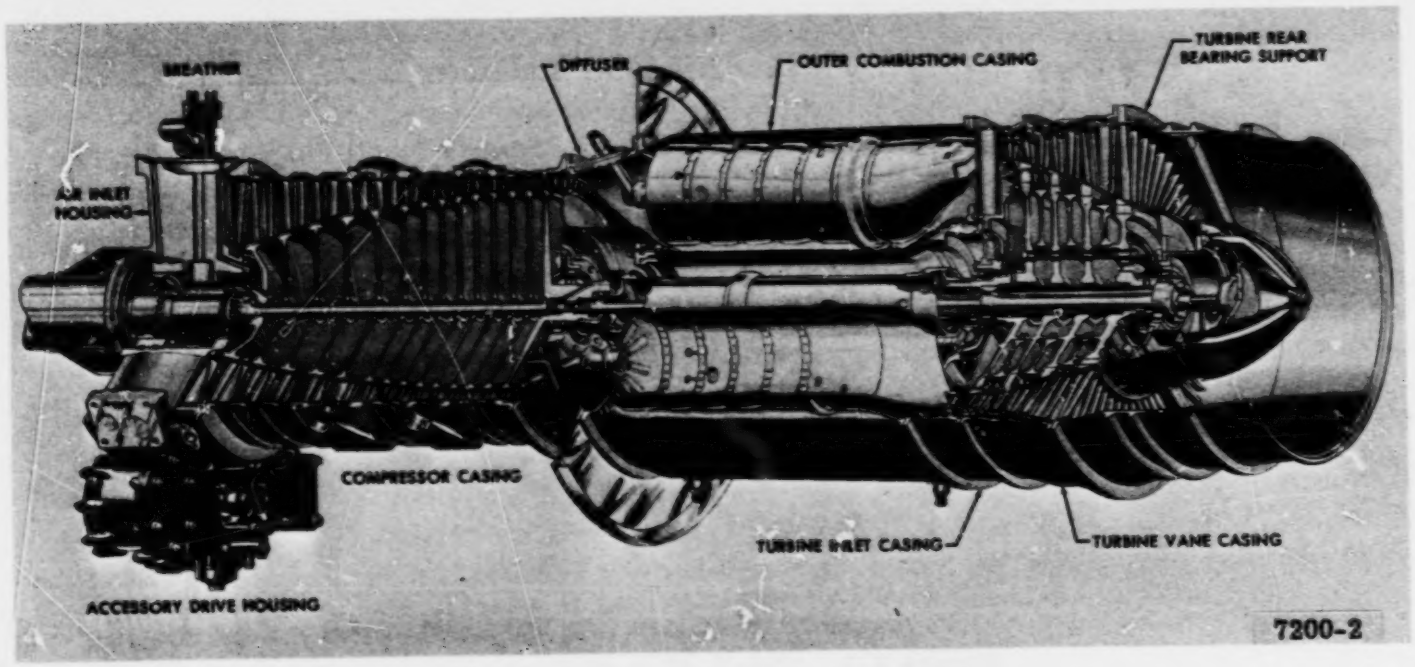

Figure 3-2. T56-A-15 engine airflow and combustion schematic.

Specific Performance

Two specific performance ratings as a function of power setting for the Allison T56-A-15 turboprop engine are summarized in Table 3-I. All performance ratings are given for standard sea level static conditions.

Table 3-I.
Allison T56-A-15 performance ratings.
(Standard sea level static conditions)

Power setting	Engine rotor speed (rpm)	Min eshp*	Compr press. ratio (R_c)	Airflow (lb/sec)	Fuel flow (lb/hr)	Turb inlet temp (°F)	Jet thrust (lb)
Normal	13,820	4365	10	33	2260	1850	760
Takeoff	13,820	4910	10	33	2460	1970	797

*Equivalent shaft horsepower

Applications

The T56-A-15 engine—a Series III version in the line of T56 models—is in quantity production as the powerplant of the Lockheed four-engine C-130 Hercules. Other T56 engines power the Lockheed P-3 Orion (a four-engine Navy ASW aircraft), the Grumman C-2 and E-2 (two-engine carrier-based Navy planes), and variations of the C-130 transport.

Two models of the Allison 501 turboprop engine are operational in commercial aircraft. The Model 501-D13 series, although no longer in production, powers the four-engine Lockheed L-188 Electra and the two-engine Convair 580. The Model 501-D22 series is used in the Lockheed four-engine commercial Hercules—the L-382 and L-100. The 501-D22A, which is the commercial counterpart of the Allison T56-A-15, is now in limited production.

Table 3-II is a listing of the Model 501 engine applications. The quantities of engines produced for commercial and military use are summarized in Table 3-III.

Table 3-II.

Allison commercial turboprop engines.

Engine model*	Power rating (eshp**)	Aircraft	Status	Remarks
501-D22A	4680	Lockheed Model 382D, E, and F transport	Limited production (3 engines on order)	
501-D22C	4680	Aero Spacelines Mini Guppy and Super Guppy outsized transports	Service only	14 engines delivered
501-D22	4050	Lockheed Model 382B transport	Service only	Engines are being converted to Model 501-D22A
501-D13	3750	Lockheed Model 188 transport	Service only	
501-D13A	3750	Lockheed Model 188 transport	Service only	Hamilton Standard propeller
501-D13D	3750	Allison Convair Model 580	Service only	
501-D13H	3750	Allison Convair Model 580	Service only	Water-alcohol augmentation for high altitude airfield performance

*Models 501-D22A & C basically the same as Military T56 Series III engines.
Model 501-D22 basically the same as Military T56 Series II engines.
Model 501-D13A, D, & H basically the same as Military T56 Series I engines.

**Equivalent shaft horsepower.

Table 3-III.
Allison turboprop engines in service.

Engine model	Type	Quantity manufactured	
501-D13 (Series I)	Commercial	1809	
T56 Series I	Military		1454
501-D22 (Series II)	Commercial	50	
T56 Series II	Military		4374
501-D22A (Series III)	Commercial	170	
T56 Series III	Military		1860
Total	Commercial	2029	
	Military		7688

PRODUCTION ENGINE TESTING

Emission measurements were taken during routine acceptance testing of Model T56-A-15 turboprop engines. The first six engines measured were run after a final run schedule; measurements of the remaining five followed an initial run. The schedules are nearly identical. Both include a power calibration run covering the entire range of engine performance. The complete test procedure is defined in Detroit Diesel Allison Production Test Specification (PTS) No. 702, Acceptance Test of Production Turboprop Engines. Data recorded during the runs included:

- Engine identification
- Date and time of day
- Test stand and operator
- Fuel flow (lb/hr)
- Torque (in.-lb)
- Shaft speed (rpm)
- Shaft horsepower (HP)*
- Compressor inlet pressure (in. Hg abs)
- Compressor inlet temperature (°F)
- Airflow (lb/sec)*
- Wet bulb temperature (°F)
- Dry bulb temperature (°F)

*Calculated from test measurements.

EMISSION MEASUREMENT

Measurement System

The measurement system used for these tests was designed to operate as an integrated system, using the SAE Preliminary Aeronautical Recommended Practice[1*] as a guide. The system was installed in production test cell No. 117 at Detroit Diesel Allison Plant No. 5 on 15 June 1971. It was used to measure the emissions—including transient and starting emissions—for this program. A schematic of the system is shown in Figure 3-3.

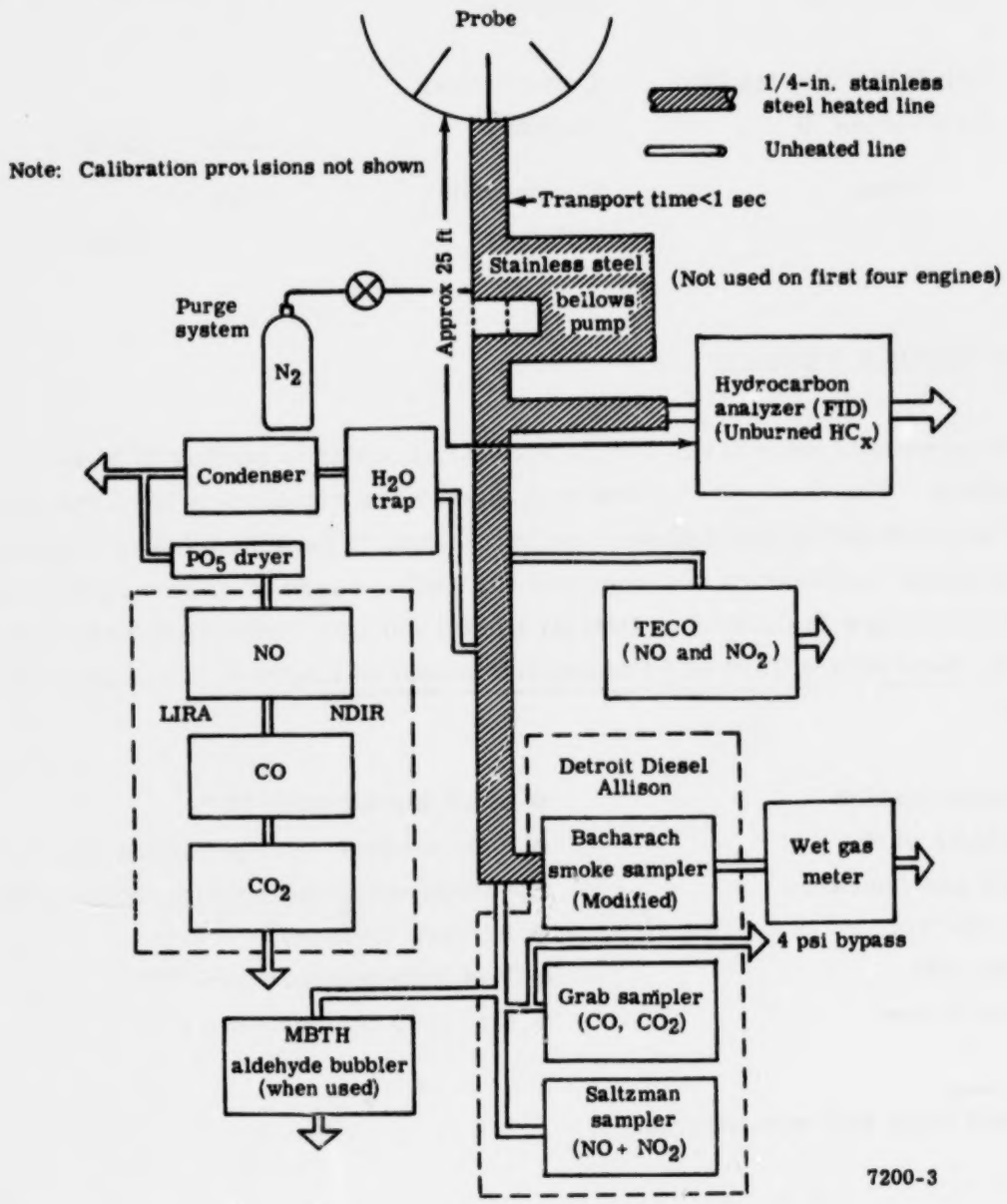

Figure 3-3. Schematic of system used for emission measurements of production T56-A-15 engines.

*Superscript numbers correspond to the references listed in Section VI of this report.

Measurements Taken

During production testing, the following measurements were taken over the full range of engine power levels. All measurement methods are described in detail in Appendix A.

- Total Hydrocarbons—Allison Heated Flame Ionization Detector (FID)
- Carbon Monoxide, Carbon Dioxide, and Nitric Oxide—Mine Safety Appliances, Luft-type Infrared Analyzers (LIRA)
- Nitric Oxide (NO) plus Nitrogen Dioxides (NO_2)—Modified Saltzman wet chemical analysis
- NO and NO_2—Thermo Electron Co. chemiluminescent analyzer
- Smoke—Bacharach smokemeter, modified to comply with ARP1179[2]
- Aldehydes—MBTH method wet chemical analysis

Figure 3-4 is a photograph of these instruments installed in the test stand corridor. The analyzer console of the FID and the calibrating gas cart are shown in Figure 3-5, the LIRA cart in Figure 3-6, the FID remote burner and oven in Figure 3-7, the smoke and grab sample panel in Figure 3-8, and the on-line L&N recorders in Figure 3-9.

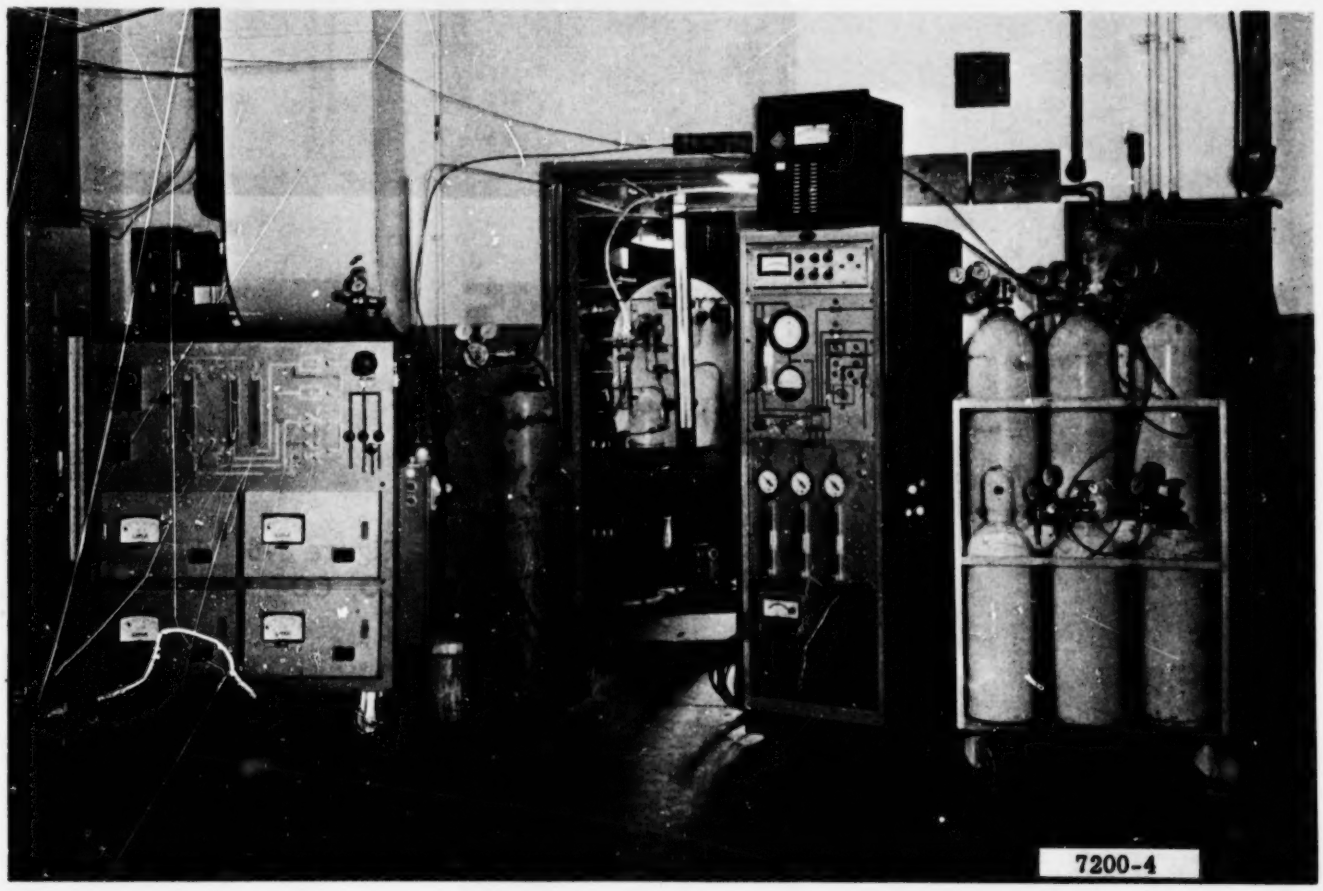

Figure 3-4. Installation of test instrumentation.

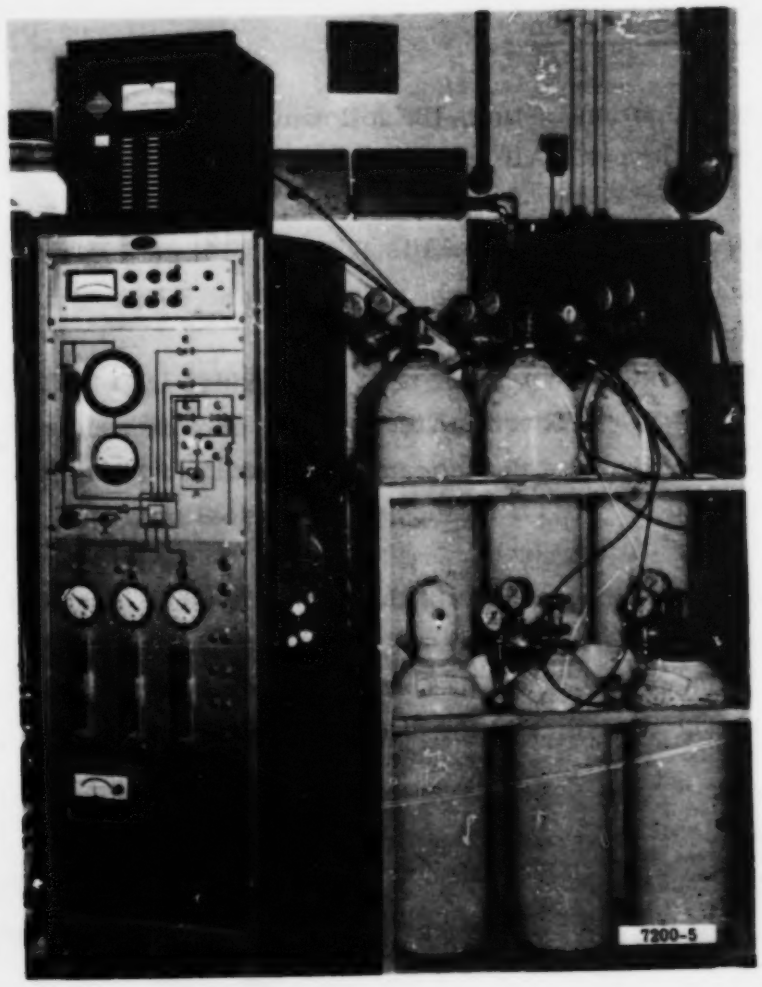

Figure 3-5. Hydrocarbon analyzer and calibrating gas cart.

Figure 3-6. LIRA cart with CO, CO_2, and NO analyzer.

Figure 3-7. Hydrocarbon analyzer remote burner-oven.

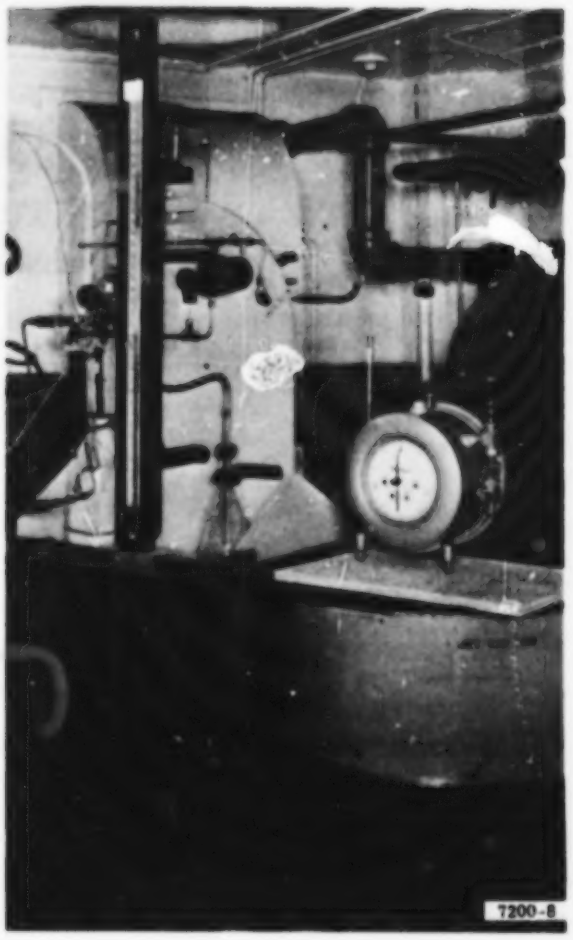

Figure 3-8. Smokemeter and grab sample panel.

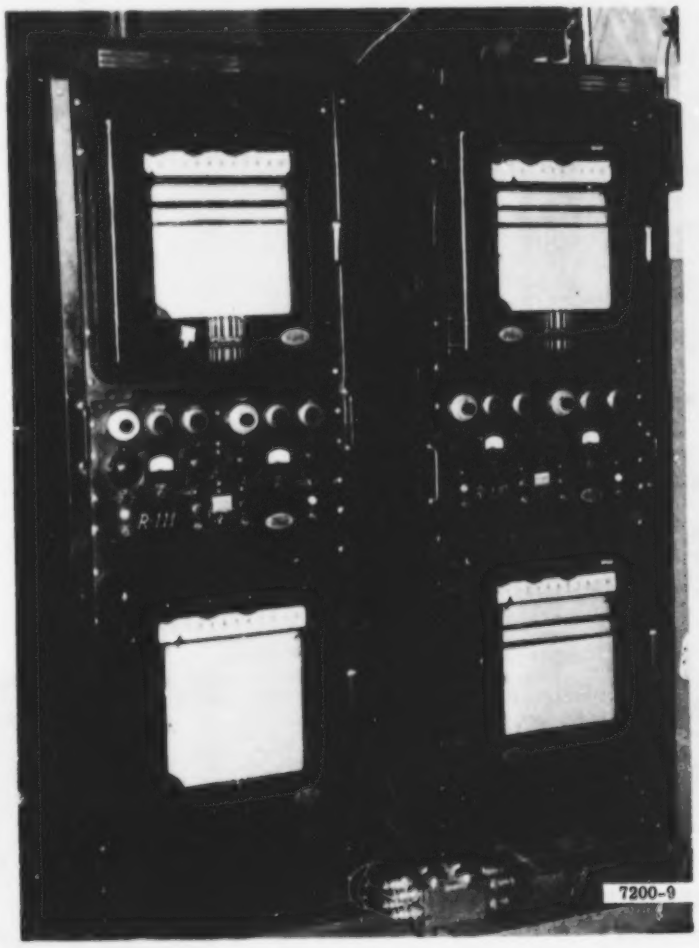

Figure 3-9. On-line strip chart recorders.

Sampling

Probe

A representative sample was obtained with a 28-hole sampling probe supplied by Detroit Diesel Allison. The probe was designed to minimize sampling error; it accounts for radial discrepancies by sampling at the area center of four equal annular areas in the tailpipe. Circumferential discrepancies were avoided by using seven probe legs to sample a six-combustor engine. The probe clamped directly to the T56 tailpipe flange but had negligible effect on engine performance. Validity of the sample was proved by carbon balance (carbon into the engine as fuel is equated to measured carbon out) which showed preliminary agreement of 5%. Results of a more detailed analysis (refer to Section IV of this report) showed even closer agreement. Figures 3-10 and 3-11 show how the probe was attached to the engines for testing.

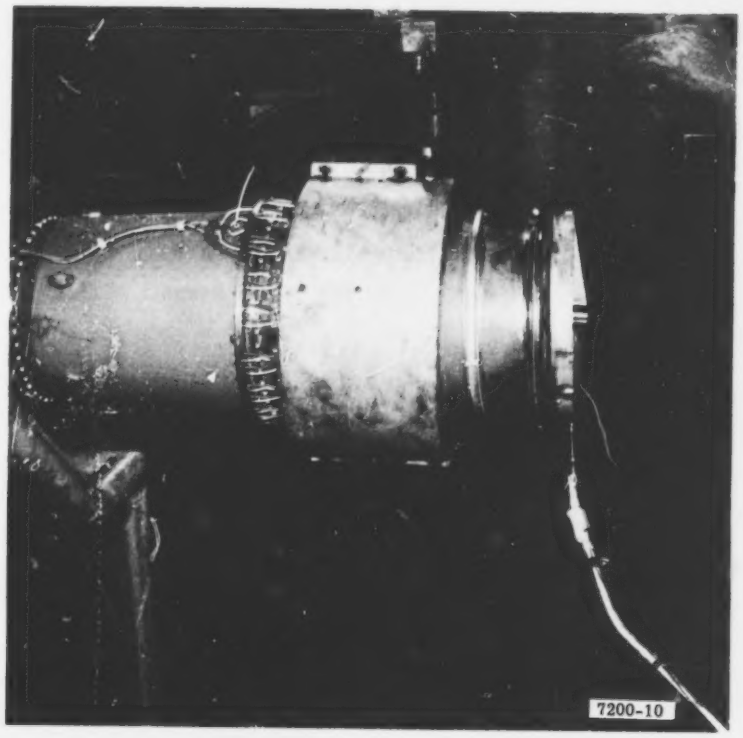

Figure 3-10. Probe and sampling line installed on T56-A-15 engine.

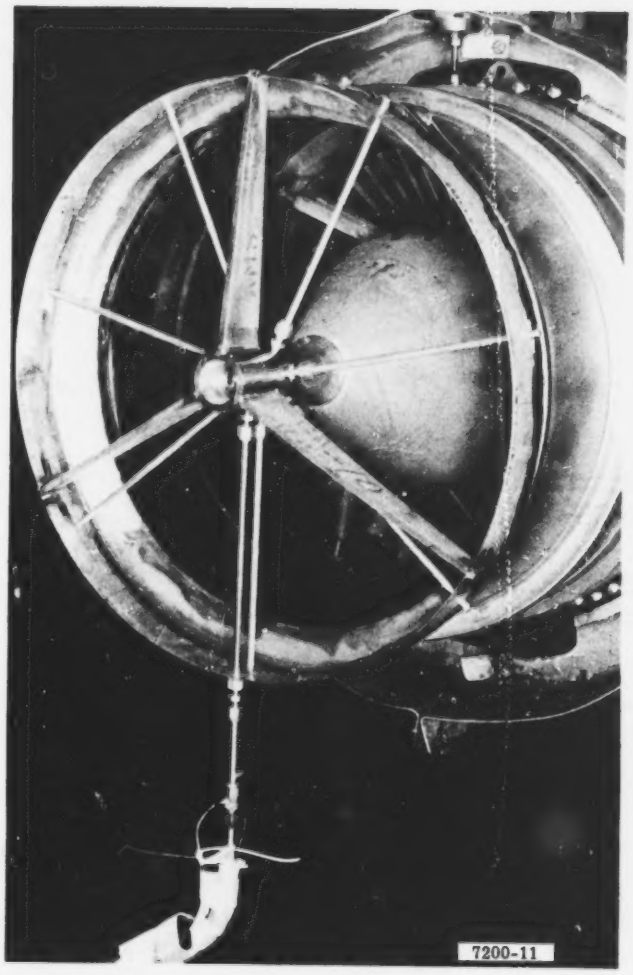

Figure 3-11. Rear view of probe and sampling line installed on T56-A-15 engine.

Lines

Heated sample lines were used throughout the tests between the engine and the FID and the engine and the smokemeter. Lines were made of 0.250-in. stainless tubing; they were wrapped with Teflon tape, 480-watt electrical heating tapes, woven asbestos sleeving, and again with Teflon tape. The tube sections were joined with instrumented unions or tees for monitoring line and gas temperatures. Th- detailed construction is shown in Figure 3-12.

Approximately 25 ft of heated line were required to reach the FID, and eight additional feet conveyed the sample to the smokemeter-Saltzman-grab sample rig. Unheated 0.250-in. stainless steel tubing was run to the LIRA cart. Flexible 0.187-in. nylon line connected the aldehyde and TECO rigs when used. The sample line was run either horizontally or downward; no upward bends were required. Two Variacs in the FID cabinet and one external unit furnished power to the four line heaters which were maintained at 300 ±10°F.

The heated line is the one running horizontally just above the FID cabinet in Figure 3-7 and can be seen at the engine in Figure 3-10.

Flow Rates and Temperatures

On the first four engines tested, sample flow was marginal at all except high power test points. Subsequent to the fourth engine, a 1.0-scfm stainless steel syphon bellows pump was installed between the probe and the FID inlet (Figure 3-3). The pump body was heated and insulated similar to the sample line. This pump permitted simultaneous operation of all instruments

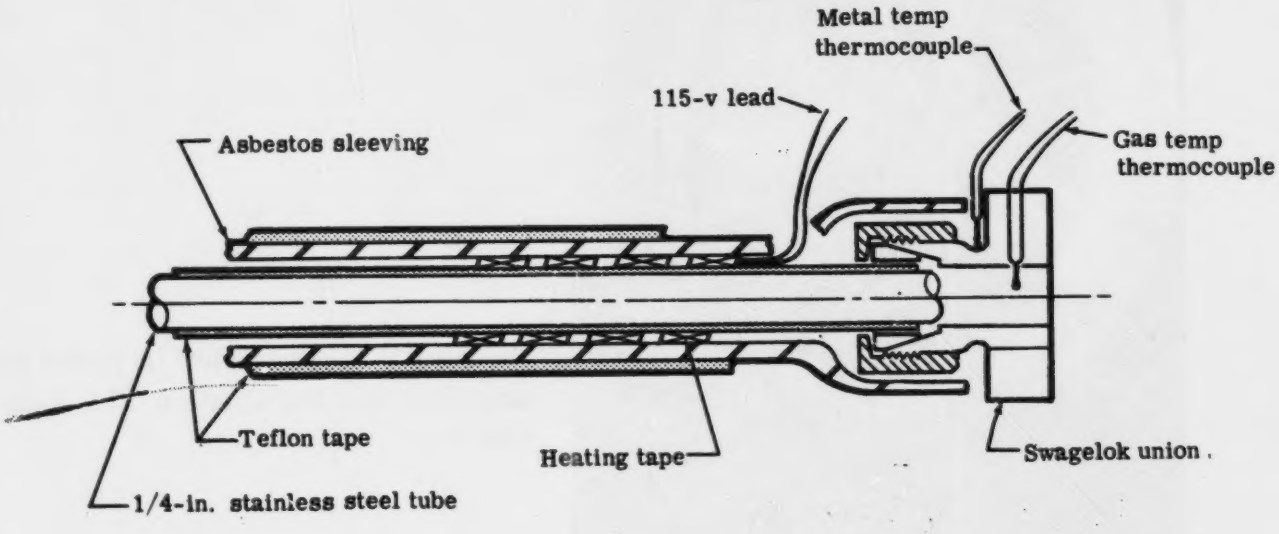

Figure 3-12. Heated sample line construction.

except the FID, which required careful pressure and flow adjustments, and provided sufficient sample flow at all power settings.

Valves

Shutoff valves in the sample lines were Hoke Roto-Ball units with their 0.375-in. NPT openings reduced to 0.250-in. Swagelok fittings. Valves on the Saltzman rig were 0.250-in. Hoke Swagelok needle valves with toggle operators. Internal shutoff in the FID was an electrically operated Hoke Roto-Ball unit, and flow regulation was provided by a motor-operated needle valve. Adjustable relief valves furnished overpressure protection in the FID, LIRA, smoke, and Saltzman rigs. Nominal settings were 4 to 5 psig.

Purge System

Purge capabilities using bottled nitrogen were provided to prevent fouling of the sample lines during starts and when no data were desired. A 200-ft^3 cylinder of nitrogen and the necessary valving were used to introduce the purge gas at the LIRA cart initially and at the bellows pump inlet after its installation.

Instrument Calibration

Shown at the right in Figure 3-5 is the portable cart containing the calibration gas bottles. The fuel, air, and hydrogen for the FID were also supplied from this cart. Sufficient regulators were available to minimize the time required to switch gases.

Flexible tubing was run from a central bottle cart for calibration of all instruments. The following gases were available for calibration purposes:

CO_2—1.02% and 5.78%
CO—52.2, 310, and 514 ppm
NO—21.5, 55.2, and 154 ppm
CO_2 + CO—3.61% plus 560 ppm
HC_x—4.27 ppm CH_4; 10.4, 105, and 203 ppm C_3H_8

Automatic Data Recording

The "on-line" outputs of analyzers during calibration and data acquisition were connected to separate L&N Speedomax strip chart recorders. A chart speed of 2 in./min was standard.

TEST PROCEDURE

General

During the emission testing of the eleven engines, normal production test procedures were used except that the initial idle running was extended slightly to switch off the nitrogen purge and bring the emission equipment on the line. The emission measurement crew was in contact with the engine operator at all times during the test and was continuously advised of the engine operating condition. Except for transients, data were taken only after the engine had stabilized.

Contract requirements of ten engines were met on June 29th. One more engine was available in the June production schedule and was measured with minimum additional effort.

Exhaust Recirculation at Reverse

The original plans were to use the measured values of emissions during the reverse thrust mode. However, examination of the results of the initial engine tests showed the existence—on the test stand—of a high component of exhaust recirculation and inlet heating of +30°F. This is not characteristic of normal aircraft operations where reverse is not used below 50 knots forward speed. Hence, it was determined that reverse mode emissions could be interpolated from the normal running data, and emission measurements in the reverse mode were dropped after the first four engines.

Low Speed Ground Idle

During the testing of the first four engines, unexpected low values of hydrocarbons and carbon monoxide were obtained at ground idle. A reevaluation of the ground operation of T56-powered aircraft revealed that during taxi the throttle position was at a higher rpm setting than when the aircraft was held on the ramp. The two operational modes are compared in the following tabulation.

Aircraft operation	Power setting	Equivalent shaft horsepower	Engine rpm	CO concentration (ppm vol)
Taxi	Ground idle (GI)	850 (max)	13,500	30-70
Holding	Low speed ground idle (LSGI)	160 (max)	10,000	320-450

Because holding is a significant part of the ground operation of T56-powered aircraft, the 10,000-rpm LSGI power setting was included for the last six engines tested. Measurements of all effluents were made at that power.

Measurement Procedure

Generally, measurements were made only at steady-state points. During most of these, adequate time was available to read the on-line instruments, make a zero instrument check, and reread the instruments. Grab samples for smoke, NO_x, and aldehydes were taken during the time the instruments were being zeroed. To obtain transients, the instruments were allowed to record during power level changes throughout the PTS run schedule.

Engine starts were recorded after all other measurements were completed. The hot engine starts were made approximately five minutes after shutdown. The ambient start was made the morning after an overnight soak at test stand ambient temperature.

Fuel drainage was collected from the fuel manifold drain valve after each test and averaged to obtain the drainage for each engine start. Measurement of fuel from other drain points was unnecessary because the burner case drains collect fuel only after a false start and the fuel accessory drains only after high seal wear.

TEST DATA

This subsection presents raw data from the power sections tested and the fuel analysis.

Data Tables

Appendix B contains (1) a definition of the PTS set points and (2) a matrix of raw data consisting of engine operating variables and gas composition obtained at various engine power levels. The PTS schedule requires certain sequencing and repetition of some set points. Where possible, redundant data were acquired to ensure high quality sampling. This redundancy is obvious on observation of the data matrix. Every effort was made to acquire data at all of the desired set points.

Fuel Drainage

Fuel drainage values were measured for each engine tested. The results were:

Engine	Fuel drainage (cc)
108506	90
108508	95
108469	95
108510	105
108507	90
108509	90
108513	110
108512	90
108517	90
108518	100
108516	95

The average fuel drainage for the eleven engines tested was 95 cc.

Fuel Analysis

A complete fuel analysis was made on the fuel used during test of Engine 108517. The results were:

Flash point, °F	-20 to -25
Sulfur content, %	0.3
Analine point, °F	124.9
Smoke point, mm	23.7
API gravity	54.1
Heating value, Btu/lb	18,687
Initial boiling point, °F	152
5%	203
10%	217
20%	231
30%	248
40%	263
50%	283
60%	310
70%	346
80%	383
90%	434
95%	464
End point, °F	481
Residue, %	1.0
Loss, %	1.0
Recovered, %	98.0

PARTICULATE EMISSIONS

Particulate measurements from previous tests of T56 engines are given in Table 3-IV. The method of measurement was the one used by the Los Angeles Air Pollution Control District, described in their Source Testing Manual,[3] in which the particulates are collected by a water bath impinger train. During the laboratory analysis, the particulates are classified as water soluble, hydrocarbon soluble, and insoluble. The sum of these fractions is the total of the particulates measured.

Table 3-IV.
Particulate emissions, T56 engines.

Data are in grains/scf of exhaust and were obtained from previous tests using JP-5 fuel.

Power setting	Test 1 T56 Series I	Test 2 T56 Series III	Test 3 T56 Series III
Low speed ground idle	0.127	0.108	---
Ground idle	0.088	---	0.112
Takeoff	0.065	0.096	---
Climb	0.092	---	---
Approach	0.088	0.071	0.076
Reverse*	0.090	---	---

*Interpolated.

STARTS AND ACCELERATIONS

Emissions were measured with on-line equipment on Engine 108518 during starting. This was the last item of testing to prevent the possibility of "hydrocarbon hangup" because of fuel in the sampling system. Three starts were run—two hot and one cold. A "hot start" is a start performed within ten minutes after shutdown. A "cold start" means that the engine has cooled to room temperature prior to a start sequence. The emissions measured during engine starting are plotted in Figures 3-13, 3-14, and 3-15.

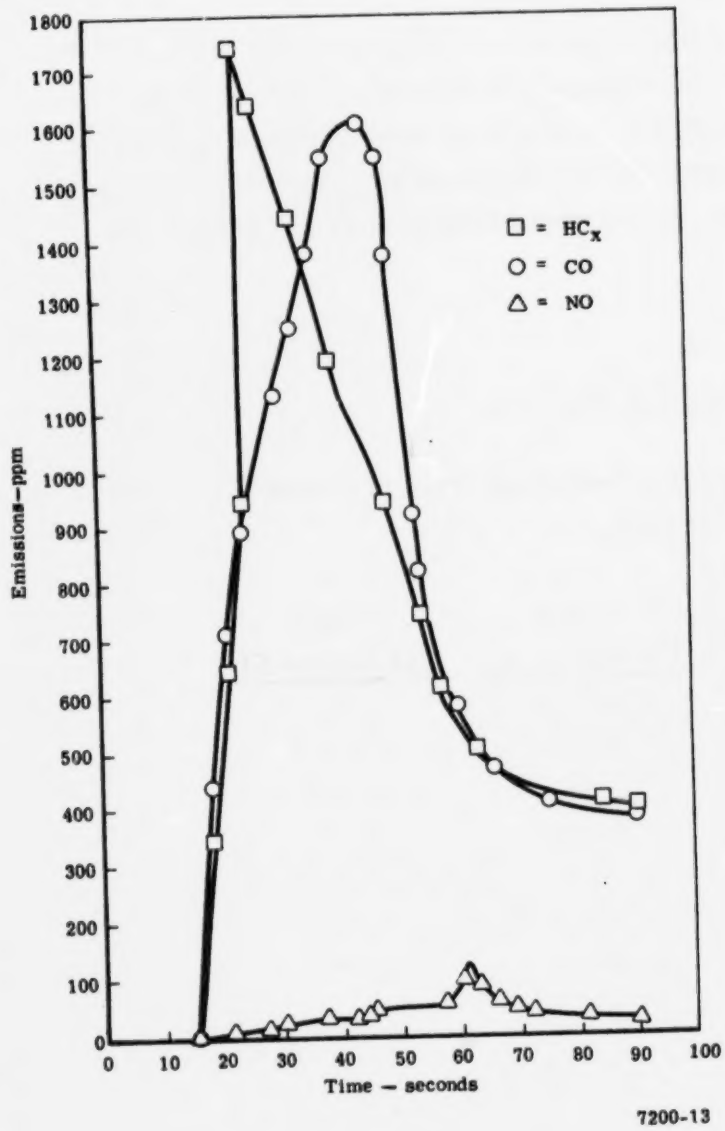

Figure 3-13. Hot start emissions (Engine 108518).

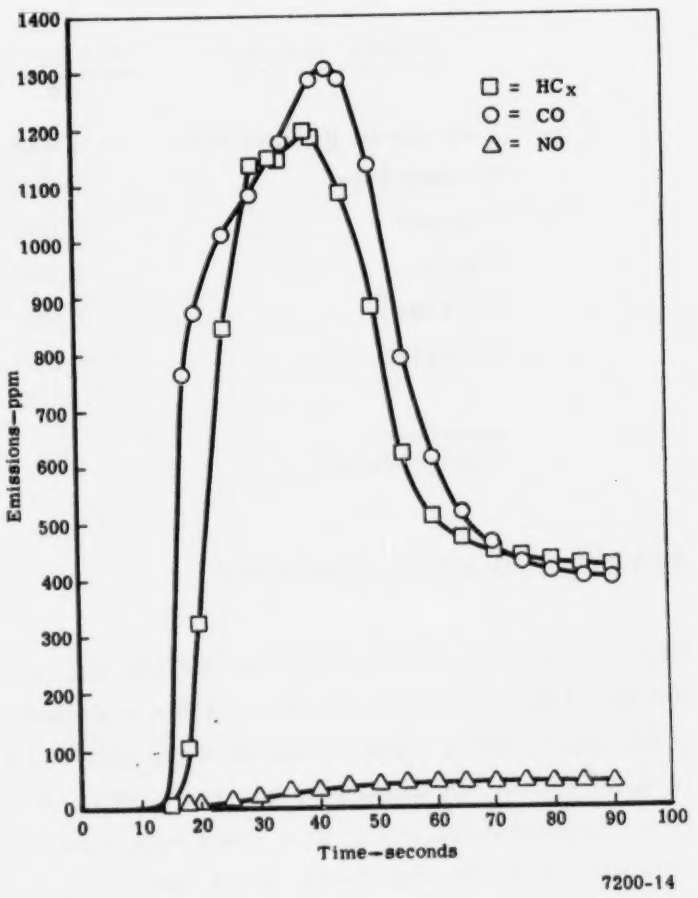

Figure 3-14. Cold start emissions (Engine 108518).

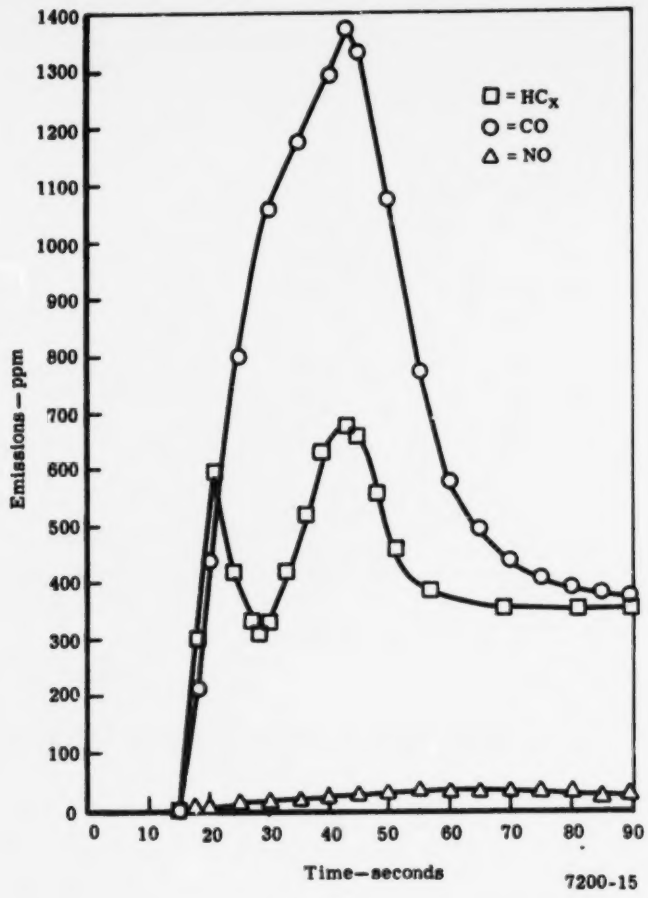

Figure 3-15. Hot start emissions (Engine 108518).

Engine acceleration and deceleration emissions were obtained during the runs of three engines. Values of total hydrocarbons, carbon monoxide, and oxides of nitrogen were obtained with the on-line equipment and are represented by the following plots:

Figure 3-16—Low speed ground idle to high speed ground idle, Engine 108517
Figure 3-17—Flight idle to takeoff, Engine 108507
Figure 3-18—Takeoff to flight idle, Engine 108512
Figure 3-19—Flight idle to takeoff, Engine 108516
Figure 3-20—Takeoff to flight idle, Engine 108516

No change in unburned hydrocarbons was observed during transients between flight idle and takeoff; therefore, they were not plotted.

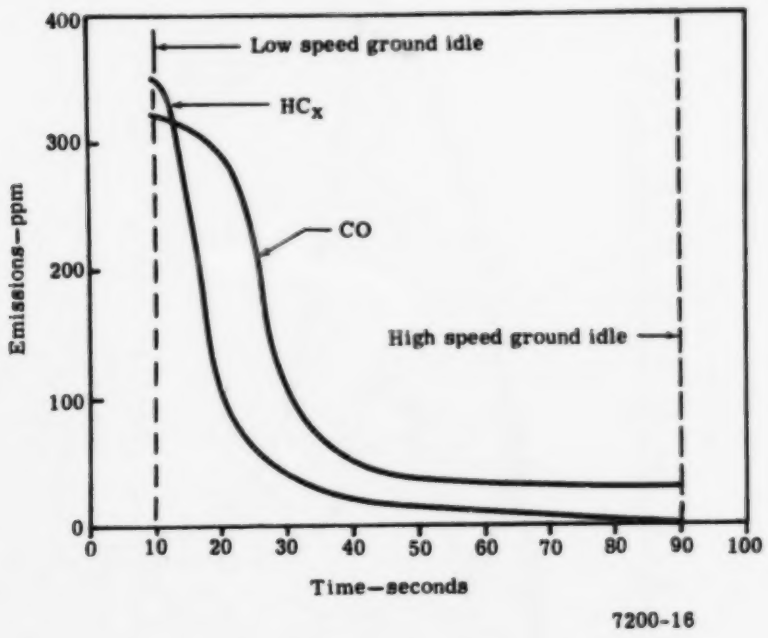

Figure 3-16. T56-A-15 emission transient data (Engine 108517).

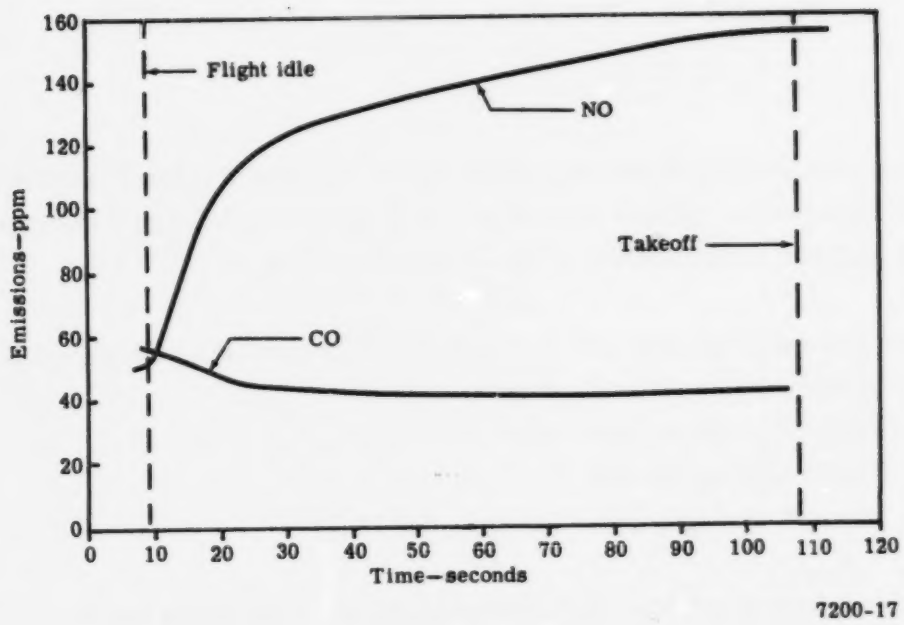

Figure 3-17. T56-A-15 emission transient data (Engine 108507).

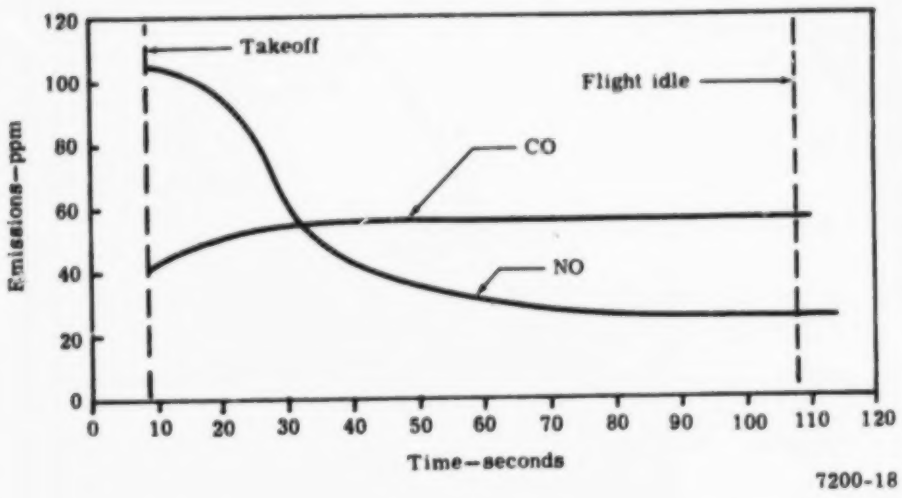

Figure 3-18. T56-A-15 emission transient data (Engine 108512).

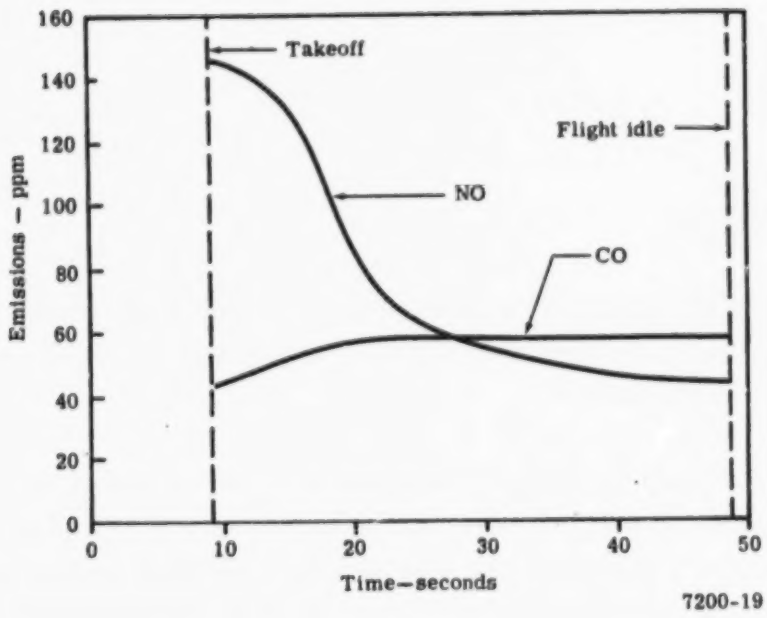

Figure 3-19. T56-A-15 emission transient data (Engine 108516).

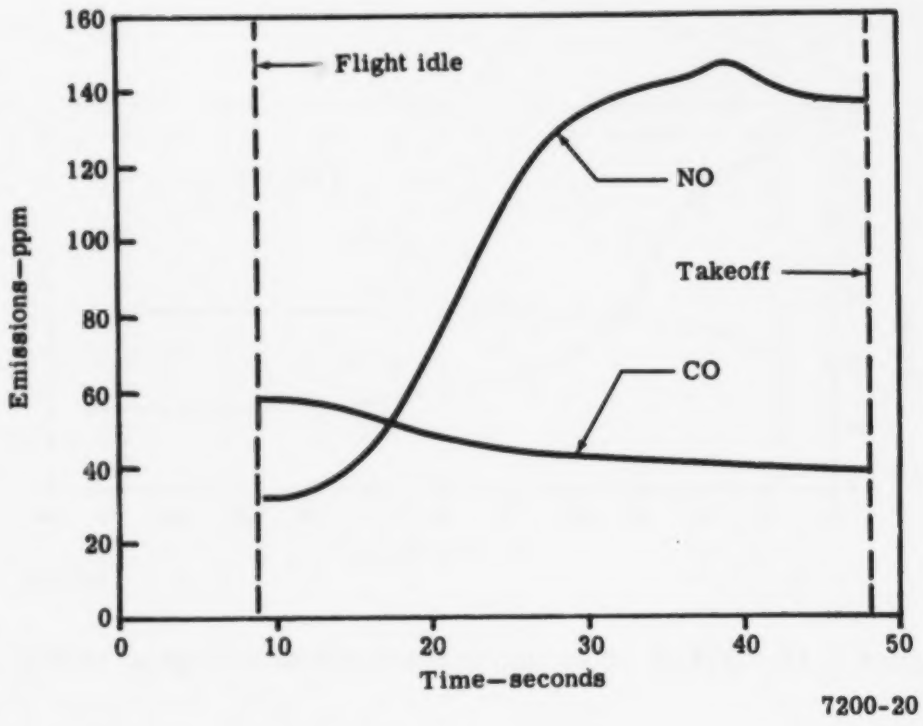

Figure 3-20. T56-A-15 emission transient data (Engine 108516).

COMMENTARY

Testing of Production Engines

No major difficulties were encountered in obtaining emissions from production engines. Considerable care was required to prevent interference with schedule requirements and with the quality of performance measurements.

During the short period of testing, the crew was able to keep up with a rate of two engines per day on one instrumented test stand; only one engine was passed because of emissions measurement equipment malfunction. However, the test schedule for each engine had to be extended because longer initial engine idle periods were needed. The experimental instrumentation and sample handling system was poorly suited to the environment of production testing which requires rapid, simple, automated procedures. These deficiencies were overcome by maximum crew effort and the use of additional manpower. One engineer and two technicians were required to take the emissions measurements. Thus, it is apparent that any aircraft turbine emission measurement system requires extensive development before it would become acceptable as a routine production testing process.

Variability of engine performance because of changes in inlet temperature to the engine and between engines can be observed in the variation in fuel flow required to reach 1970°F turbine inlet temperature—the takeoff power point:

Engine	Fuel flow (lb/hr)	Compressor inlet temperature (°F)
108513	2074	102
108517	2150	99
108508	2190	88
108507	2170	94
108506	2152	93
108509	2128	94
108516	2190	81
108518	2260	91
108512	2110	102
108510	2210	85
108469	2090	94

The mass of fuel burned is related to engine performance and inlet conditions. For future standards, it would seem reasonable to correct mass emissions values to standard inlet conditions.

The production test stand is not the ideal environment for emissions tests. The exhaust recirculation encountered at reverse thrust has been mentioned. In addition, fuel and oil spillage, oil accumulations, and hydrocarbon solvent engine washdowns for leak checks contribute to make the hydrocarbon background levels several times higher than the minimum values emitted by the engine.

Sampling and Sample Handling

The sample probe performed well throughout the testing. No maintenance or adjustment was necessary and no malfunction occurred. Two connections were required for installation of the probe—one at the clamp nut, which was lockwired, and one at the gas fitting. The total installation time was less than one minute. The probe was always indexed with the sample exit line straight down as shown in Figure 3-11.

A prime number of sampling legs (7) and a large number of sampling holes (28) were chosen to compensate for fewer sampling points and to permit a definitive traverse of the exhaust gas

signature at the rear of the engine. Carbon balance computations proved the validity of the sampling:

Carbon in = carbon out
Measured fuel and air = measured CO, CO_2, and HC_x in exhaust concentration within $^{+3}_{-0}$ %

The details of the analysis are described under the Sampling Quality heading in Section IV.

Sample flow control was difficult until after the high temperature bellows pump was delivered. This pump, installed in the sample line, isolated the instruments so that the flows were no longer sensitive to the engine operating conditions. Instrument flows were then easily held over the engine power range. However, the practice of taking grab samples between readings of the on-line system was established to reduce the number of adjustments at each of the instruments. The long run periods and the duplication of run points in the PTS made this possible.

Sample line temperatures were easily maintained by the use of Variacs to control the electrical heating tapes. No changes in settings were required once the Variac settings were determined. The heated sample line gas temperature was maintained at 300 ±10°F throughout the test.

Carbon Monoxide and Carbon Dioxide

CO and CO_2 instruments were stable and the measurements were repeatable throughout the test. However, the instrument response was low because they were connected in series behind the long-path NO instrument. Maximum values of CO occurred at LSGI; minimum values occurred at takeoff. CO_2 concentration was directly proportional to engine fuel/air ratio. Average concentration values were:

	CO (ppm vol)	CO_2 (% vol)
Low speed ground idle	377	2.86
Ground idle	57	1.59
Takeoff	37	4.55

Repeatability of the instruments is illustrated by the values obtained during repeat runs of the same engine:

Engine 108517—Takeoff power

CO (ppm vol)	CO_2 (% vol)	Fuel flow (lb/hr)
32	4.98	2150
30	4.93	2150
39	4.90	2150

Oxides of Nitrogen

The LIRA long-path infrared analyzer produced NO readings with obvious variations. Instrument noise and susceptibility to water vapor were two observed problems. Considerable effort was made to eliminate water vapor by traps and by the use of phosphorous pentoxide "Aquasorb" drier cartridges, several dozen of which were consumed during the testing. Typical maximum and minimum values of observed NO (in ppm vol) were:

Maximum (takeoff)	Minimum (ground idle)
118	40
138	37
139	21
114	24
160	29
150	32
152	30
150	46
164	24
153	31

The Saltzman wet chemistry process was run in conjunction with the LIRA NO analyzer on Engine 108513 to obtain the comparative values of NO and NO plus NO_2. A comparison of LIRA and Saltzman showed the NO_2 content to be about 1/3 of the total NO_x content in the exhaust at idle:

Power setting	Saltzman $NO + NO_2$ (ppm vol)	LIRA NO (ppm vol)	NO_2 (by subtraction) ppm vol	%
Low speed ground idle	35	23	12	34
Ground idle	34	21	13	38
Flight idle	51	37	14	27
75% normal	89	66	23	26
100% normal	126	89	37	28
Takeoff	139	123	16	12

However, as the engine power is increased, the percentage of NO_2 is reduced.

The chemiluminescent instrument (CI) was furnished by EPA for this test. A comparison of values obtained by the LIRA and the CI instruments follows.

Power setting	LIRA NO (ppm vol)	CI NO (ppm vol)	CI NO + NO_2 (ppm vol)	CI NO_2 (ppm vol)
Low speed ground idle	20	17	25	8
Ground idle	38	22	28	6
	24	20	26	6
Flight idle	32	31	38	7
	34	33	38	5
75% normal	68	68	73	5
100% normal	107	100	107	7
Takeoff	111	107	115	8
	107	115	120	5
	102	111	118	7

Agreement between the LIRA and CI instruments is within 10% in most cases. The CI instrument measures considerably less NO_2 in the exhaust (27% at LSGI and 6% at TO) than the Saltzman method.

Performance and operation of the CI instrument were excellent. It was easy to use, stable, and fast acting. A comparison of the CI and the 38-in. cell LIRA response is shown in Figure 3-21, which is plotted from the strip chart data for each instrument.

Hydrocarbons

Unburned hydrocarbon readings were close to background levels over most of the engine operating range. Background was reduced by washing the lines with solvent and back purging the heated lines until values at the start of a test run were below 20 parts per million carbon (ppm C). By the time the run was completed, levels were often doubled or trebled. Net values were determined by introduction of the calibrating gases at the probe-to-sample line connector. Average hydrocarbons were observed as:

Power setting	Average HC_x (ppm C vol)
Low speed ground idle	367
Ground idle	15
Takeoff	6

Aldehydes

Oxygenated compounds as measured by the MBTH method showed low levels (less than 1 ppm) except at LSGI which was measured at 3 ppm. All levels less than 1 ppm were reported as one rather than zero. The method is laborious, requiring five minutes to obtain a sample, and does not appear to give acceptable sensitivity below 1 ppm. However, no better methods are known at this time.

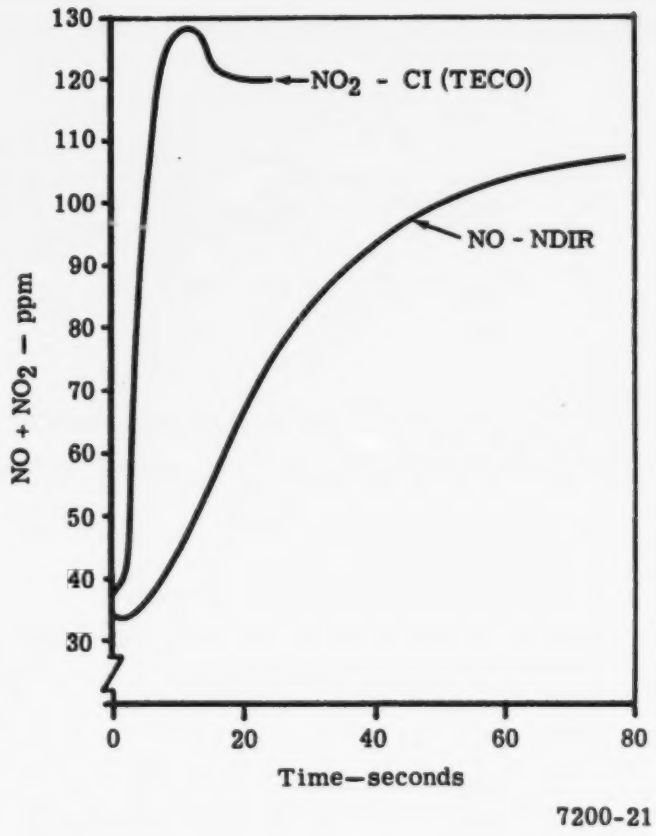

Figure 3-21. T56-A-15 emission transient data (Engine 108517).

Smoke

Good agreement in smoke measurements throughout the test is attributed in part to the large number of sampling points. Smoke values ranged from S/N 41 at LSGI to a maximum single reading of 62 at flight idle. Generally, smoke values were nearly constant over the flight range with the maximum at takeoff. Average values were:

Power setting	S/N
Low speed ground idle	42
Flight idle	54.5
Takeoff	56

Particulates

Particulate measurements are arduous, expensive, and impractical to make on production engines. Measurements had been made prior to this program on experimental engines with the following results. The method used has been the subject of much discussion because of the unknown character of the material in a water-soluble leg. In these tests, the volumes in each leg at LSGI and TO were:

	Distribution		
Power setting	H_2O soluble (%)	HC_x soluble (%)	Insoluble (%)
LSGI	45	37	18
TO	29	32	39

Comments concerning this method and the questionable significance of the results it produces were made by the Coordination Research Council in their report on measurement techniques.[4]

Transients

Starting transients were evaluated by integration of the concentration-time curves of Figures 3-13, 3-14, and 3-15. The results for Engine 108518 were:

	Concentrations (ppm sec)		
	Hot start	Cold start	Hot start
CO	62,400	60,000	56,800
HC_x	59,200	52,000	32,400
NO	3,000	2,240	2,120

The CO and NO measurements are dry—i.e., without correction for water in the exhaust.

An electrical spike (noise) was observed at the onset of transients from all the LIRA instruments. No explanation is attempted for this phenomenon but it is mentioned to avoid anticipated problems if results were linked directly into computers from this type of instrument.

Acceleration and deceleration transient values were small—essentially a blending between the two power levels—as shown in Figures 3-16 through 3-20. This is typical of most aircraft turbine engines where control of the acceleration and deceleration fuel schedule is precise. A comparison of transient mass emissions with those of the steady-state LTO cycle is given in Section IV, Analysis.

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IV. ANALYSIS

GENERAL APPROACH

Equipment was provided to carefully monitor exhaust gas composition of T56-A-15 production engines during the production test schedule operation. A matrix of data consisting of operating variables of the engine and gas compositions was obtained at various levels of engine power. These raw observations were converted into corrected values (e.g., from dry LIRA measurements to actual basis), and correlating (regression) equations which express pollutant concentrations as functions of engine operating variables were determined. Applicable correlating equations were then used to compute pollutant concentrations for each mode of the required LTO mission defined subsequently under the LTO Cycle heading. The approach taken here enables computation of the pollutant values of CO, HC_x, NO_x, and CO_2 over the entire T56-A-15 engine range of sea level operations.

Summary tables are provided which display pollutant values over the LTO mission in various units. Mean values of each component are computed along with their associated standard deviations.

ENGINE TEST CYCLES

The engine was run over a production test specification (PTS) schedule during acceptance testing. Data thus obtained were converted to the emission test cycle (Landing-Takeoff or LTO cycle) which was supplied by Detroit Diesel Allison based on T56 (Model 501) service experience.

PTS Cycle

In order to obtain emission data without interfering with contractual engine production obligations, measurements were taken during normal acceptance testing according to the PTS. The schedule and sequence varies slightly, depending on whether the initial or final run of the acceptance test is being made. A teardown inspection is made between the initial and final runs. Emissions measurements were made only during the power calibration portion of the test which was run after control adjustments, leak checks, and seal break-in runs, thereby ensuring that the measurements were made from engines that had demonstrated acceptable performance. The PTS schedule for the T56-A-15 engine final runs is illustrated in Figure 4-1.

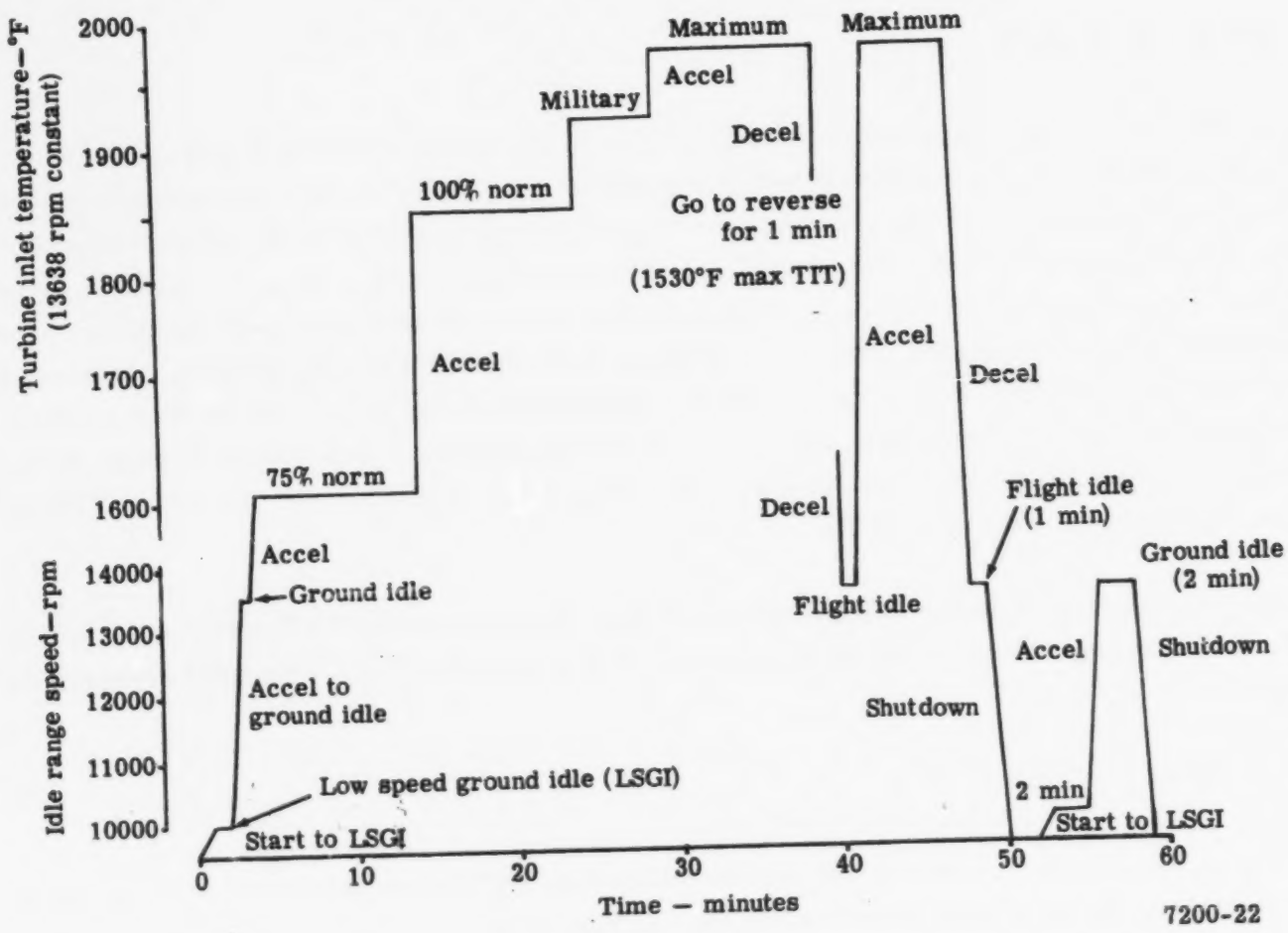

Figure 4-1. T56-A-15 production test specification run schedule.

LTO Cycle

A short study of the operational profiles of T56 (501)-powered aircraft in the airport environment was made by the Detroit Diesel Allison Service Department. Only the L-100 and L-382 Hercules, the L-188 Electra, and the Convair 580 were considered. The study was also limited to normal airline operations in North America, to a standard day, and to maximum allowable operating weights of the aircraft. Only those operations below 3000 ft above terrain were considered. The resulting profiles were quite similar and were combined into an LTO cycle representative of a Model 501 turboprop engine-powered aircraft.

Taxi-idle operations were specifically reviewed in detail because of the relatively large mass emissions contribution of the low speed ground idle (LSGI) power point which is run at 10,000 rpm with the compressor bleeds open. It is used whenever the aircraft is held stationary on the ramp or at the dock. The LTO cycle evolved from the study is summarized in Table 4-I.

Table 4-I.
Representative landing-takeoff cycle for Model 501 turboprop aircraft.

Mode No.	Mode description	Mode time (min)	Engine power	Engine rpm	Turbine inlet temp (°F)	Fuel flow (lb/hr)	Fuel/air ratio
1	Holding—outbound	4.0	Low speed ground idle	10,000	1200	565	0.013
2	Taxi—outbound	2.0	High speed ground idle	13,500	1070	670	0.0075
3	Takeoff	0.5	Takeoff	13,800	1970	2175	0.0225
4	Climb out	2.5	Near 90% normal	13,800	1850	1870	0.019
5	Approach	4.6	Near flight idle	13,800	1200	860	0.010
6	Reverse	0.167	Reverse	13,800	1610	1390	0.0155
7	Holding—inbound	4.0	Low speed ground idle	10,000	1200	565	0.013
8	Taxi—inbound	2.0	High speed ground idle	13,500	1070	670	0.0075

DATA ANALYSIS

An overall schematic diagram of the data handling process used herein is illustrated in Figure 4-2.

General Preparation

Test programs pose inherent problems in acquiring complete sets of data. Mechanical malfunctions, instrument failure, operators, etc, all contribute to potential data matrix gaps. Subsequently, these gaps cannot be ignored, nor can zero be substituted in the matrix in lieu of data. Therefore, the missing data items were filled with reasonable and expected quantities to complete the data matrix. This procedure was incorporated during the raw data conversion. However, in retrospect, the effects of this device were found to be completely submerged by the natural dispersion of the whole data population.

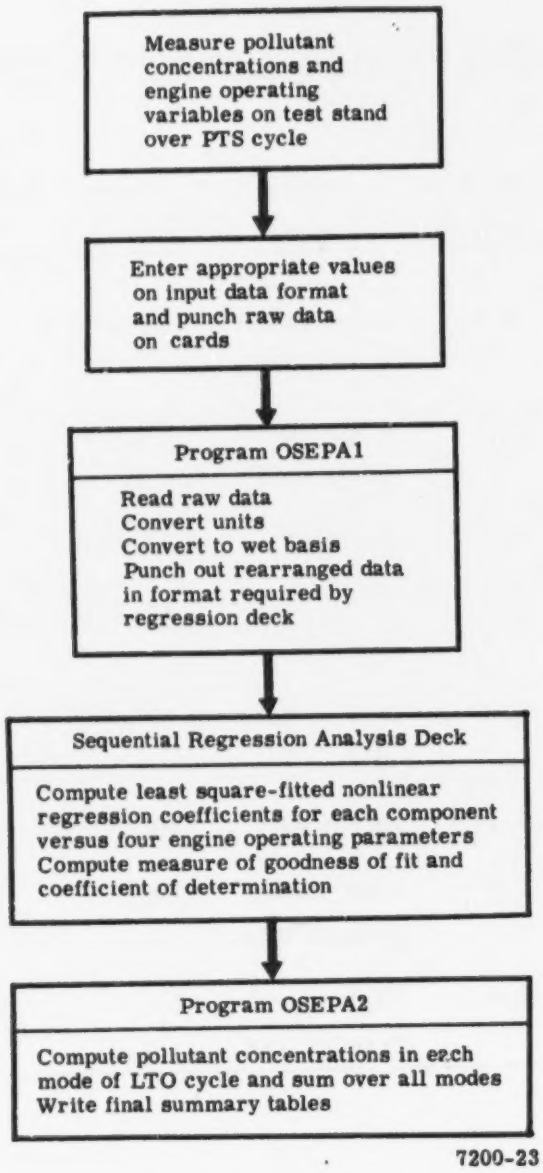
Measure pollutant concentrations and engine operating variables on test stand over PTS cycle
Enter appropriate values on input data format and punch raw data on cards
Program OSEPA1
Read raw data
Convert units
Convert to wet basis
Punch out rearranged data in format required by regression deck
Sequential Regression Analysis Deck
Compute least square-fitted nonlinear regression coefficients for each component versus four engine operating parameters
Compute measure of goodness of fit and coefficient of determination
Program OSEPA2
Compute pollutant concentrations in each mode of LTO cycle and sum over all modes
Write final summary tables
7200-23

Figure 4-2. Schematic diagram of data handling process.

Regression Analysis

Preliminary examination of the raw data early in the effort showed that the following engine parameters were the only ones required in the nonlinear regression equations considering the sample size and quality of measurements. The independent variables, then, are:

- Turbine inlet temperature (TIT)
- Fuel/air ratio (F/A)
- Output horsepower (HP)
- Reciprocal horsepower (1/HP)

It follows that any pollutant concentration, y, is expressable in terms of these independent variables by a regression equation of the form:

$$y = A_1 + A_2 \cdot TIT + A_3 \cdot F/A + A_4 \cdot HP + A_5/HP \quad (1)$$

The coefficients in Equation (1) are unique for each component in each engine.

In order to define the required independent variables, the measurements shown in Table 4-II were observed for each engine and entered on the raw data input format. Because of the constant-speed characteristics of the T56 engine, total engine airflow in pounds per second can be defined for all test points except LSGI by specifying compressor air inlet temperature and ambient pressure at the engine air inlet test bell.[6] Appendix D gives these airflow values. For the 10,000-rpm LSGI operating point, airflow (W_a) was defined by Equation (2):

$$W_a = 22.1566 - 0.001244\,(459.74 + TIT) \quad (2)$$

Horsepower was computed in the standard manner as shown by Equation (3):

$$HP = 0.158682 \cdot iTORQ \cdot iRPM. \quad (3)$$

Observed concentrations from the raw data (corrected to wet basis in the case of CO, NO_x, and CO_2) were then fed into the sequential regression analysis step where all the regression coefficients, A_i, of Equation (1) were computed using an algorithm described by M. A. Efroymson.[5] For each regression Equation (1), a quantity labeled S(y) is produced which may be approximately interpreted as the ± one-sigma band on the computed values of concentrations from Equation (1). It should be emphasized that the regression equations defined herein play a dual role in the analysis. First, they serve to show how sensitive a given concentration is to each of the engine variables (TIT, F/A, HP, or 1/HP). Second, they serve as smoothing and interpolating functions for pollutant concentrations at operating points other than those observed in the raw data. This latter property is essential since the raw measurements were made at points in the space (TIT, F/A, HP) which do not correspond with points required for the LTO mission cycle. Appendix E is a listing of all regression coefficients, A_i, for all components measured on all engines in addition to S(y) for each case, and N—the number of observations used in the particular regression. The column labeled R^2 contains values of the coefficient of determination for each regression. The square root of R^2 is the coefficient of multiple correlation. Commonly, R^2 is referred to as the fraction of variation in the observed values of the dependent variable which is accounted for by the given regression equation. An R^2 value of 1.0 implies a perfect functional fit.

Table 4-II.
Dictionary of raw input data.

FORTRAN label	Format	Description	Unit
iDATE	i3	Date of measurement (e.g., 716 means July 16)	none
iENG	i4	Last four digits of engine serial number	none
GF	i1	Label G or F denoting "green" run on engine or "final" run on engine	none
iSET	i2	Setting number of engine test cycle	none
iRPM	i3	RPM/100	rpm/100
iWF	i4	Fuel flow	lb/hr
iTORQ	i3	Actual engine torque/100	in.-lb/100
iTIT	i4	Turbine inlet temperature	°F
iCIT	i3	Compressor inlet temperature	°F
iHUM	i2	Relative humidity of inlet air	%
iCO	i4	Measured CO concentration (dry basis—LIRA)	ppm vol
iCO_2	i3	Measured CO_2 concentration (dry basis—LIRA)	% vol × 100
iNO_1	i3	Measured NO_x (as NO_2) (dry basis—LIRA)	ppm vol
iHC_x	i4	Measured HC_x (as C) (as-is basis—FID)	ppm vol
iSMOK	i2	Measured smoke index (smoke number—S/N)	none
iCHO	i4	Measured aldehydes as formaldehyde	ppm vol
iSALT	i3	Measured NO_x (as NO_2) by Saltzman wet method	ppm vol
iNO_2	i4	Measured NO (as NO) by chemiluminescent analyzer	ppm vol
$iNONO_2$	i4	Measured total NO + NO_2 by chemiluminescent analyzer	ppm vol
iPRES	i3	Ambient barometric pressure	in. Hg × 10

The conversion of dry concentrations to the wet basis is made using equations and procedures recommended by an SAE study committee.[1] These are given in Appendix C.

RESULTS

Final summary results for the regression analysis for each of the eleven engines are given in this subsection. Carbon dioxide values are computed to lend confidence to the quality of exhaust gas sampling and to show combustion efficiency.

Concentrations computed from regression equations for LTO points may occasionally be negative, so logic has been incorporated into the computer program to set such values to zero because negative weights are clearly not admissible.

Regression Analysis

All regression coefficients, A_1 through A_5, the pseudostandard deviation, S(y), the coefficient of determination, R^2, and the number of observations, N, on each engine examined are summarized in Appendix E.

R^2 values for CO_2 regressions are always extremely high because CO_2 must correlate well with fuel/air ratio. The other components—CO, HC_x, smoke, and NO_x—nearly always have R^2 values well above 0.9. R^2 values from Engine 108512 illustrate this. Dispersion values, S(y), are typically about what one might expect from analytical errors of the measuring instruments.

Component	R^2
CO_2	0.999998
CO	0.978
HC_x	0.959
Smoke	0.976
NO_x	0.898

LTO Computation

Table 4-III shows the basic mass emission performance for each T56 engine. All other summary tables are derived from this master. Pollutants CO, NO_x, HC_x, and CO_2 are each reported three ways for each mode of the mission—viz:

- lb/1000 lb fuel (LB/TPF)
- lb/hr
- lb for mode

The columns of pounds in mode are then summed over all modes to give measured pounds pollutant over the whole eight-mode mission. One such table is printed for each engine.

The results of Table 4-III are condensed in Table 4-IV which lists total pounds of each pollutant (over the LTO mission) for each engine. It also gives mean values of pounds of pollutant over the sample of all engines and the standard deviation of each pollutant from the sample mean. A second set of means and standard deviations is computed over the deleted sample of seven engines for which actual ground start mode was measured. In the table, those engines labeled with an asterisk are those which use the CO, HC_x, and NO regressions belonging to

Engine 108512 inasmuch as no LSGI data were taken for these units. This arbitrary insertion of data was done only in the interest of "rounding out" the sample and, as seen in the values labeled "mean (7)" and "$\pm \sigma$ (7)" has some effect on the rounded-out sample mean. Note that all three "mean (7)" values lie well within the one-sigma band of the means over eleven engines. This suggests that the bias introduced by rounding out is not large and the mean of the sample of eleven engines is validated.

Table 4-III.

Emission performance summary.

LTO CYCLE T56 ENGINE NUMBER 8509

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1200	10000	4.000	565	32.6	18.4	1.227	3.472	1.962	0.131	14.36	8.12	0.54	3048.2	1722.2	114.8
2	1070	13500	2.000	670	13.9	9.3	0.311	6.814	4.565	0.152	5.22	3.49	0.12	3106.2	2081.2	69.4
3	1970	13800	0.500	2175	1.5	3.3	0.028	10.523	22.888	0.191	0.08	0.17	0.00	3141.9	6833.6	56.9
4	1850	13800	2.500	1870	1.8	3.4	0.143	10.971	20.517	0.855	0.11	0.20	0.01	3141.3	5874.2	244.8
5	1200	13800	4.600	860	0.5	0.4	0.034	7.870	6.768	0.519	0.0	0.0	0.0	3143.7	2703.6	207.3
6	1610	13800	0.167	1390	1.6	2.3	0.006	10.116	14.062	0.039	0.0	0.0	0.0	3141.9	4367.3	12.2
7	1200	10000	4.000	565	32.6	18.4	1.227	3.472	1.962	0.131	14.36	8.12	0.54	3048.2	1722.2	114.8
8	1070	13500	2.000	670	13.9	9.3	0.311	6.814	4.565	0.152	5.22	3.49	0.12	3106.2	2081.2	69.4
					TOTAL CO =		3.287	TOTAL NOX =		2.170	TOTAL HCX =		1.325	TOTAL CO2 =		889.5

LTO CYCLE T56 ENGINE NUMBER 8516

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1180	10000	4.000	560	29.0	16.2	1.083	0.716	0.401	0.027	14.90	8.34	0.56	3052.1	1709.2	113.9
2	1070	13500	2.000	670	9.9	6.6	0.221	6.137	4.111	0.137	1.23	0.82	0.03	3125.1	2093.8	69.8
3	1970	13800	0.500	2175	5.3	11.5	0.096	10.859	23.618	0.197	1.92	4.18	0.03	3130.2	6808.1	56.7
4	1850	13800	2.500	1870	1.4	2.6	0.110	8.354	15.621	0.651	0.22	0.42	0.02	3141.6	5874.8	244.8
5	1200	13800	4.600	860	5.1	4.4	0.338	5.626	4.838	0.371	0.02	0.02	0.00	3136.4	2697.3	206.8
6	1610	13800	0.167	1390	1.5	2.0	0.006	5.741	7.979	0.022	0.15	0.21	0.00	3141.7	4367.0	12.2
7	1180	10000	4.000	560	29.0	16.2	1.083	0.716	0.401	0.027	14.90	8.34	0.56	3052.1	1709.2	113.9
8	1070	13500	2.000	670	9.9	6.6	0.221	6.137	4.111	0.137	1.23	0.82	0.03	3125.1	2093.8	69.8
					TOTAL CO =		3.157	TOTAL NOX =		1.568	TOTAL HCX =		1.221	TOTAL CO2 =		887.9

LTO CYCLE T56 ENGINE NUMBER 8518

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1160	10000	4.000	560	25.5	14.3	0.952	4.229	2.368	0.158	14.67	8.21	0.55	3058.3	1712.7	114.2
2	1070	13500	2.000	670	7.9	5.3	0.177	5.597	3.750	0.125	0.45	0.30	0.01	3130.6	2097.5	69.9
3	1970	13800	0.500	2175	2.3	5.0	0.041	8.037	17.480	0.146	0.75	1.62	0.01	3138.6	6826.4	56.9
4	1850	13800	2.500	1870	0.4	0.7	0.028	8.528	15.948	0.664	0.0	0.0	0.0	3144.0	5879.2	245.0
5	1200	13800	4.600	860	3.2	2.7	0.210	6.176	5.311	0.407	0.0	0.0	0.0	3139.5	2700.0	207.0
6	1610	13800	0.167	1390	1.0	1.4	0.004	8.054	11.195	0.031	0.0	0.0	0.0	3142.9	4368.7	12.2
7	1160	10000	4.000	560	25.5	14.3	0.952	4.229	2.368	0.158	14.67	8.21	0.55	3058.3	1712.7	114.2
8	1070	13500	2.000	670	7.9	5.3	0.177	5.597	3.750	0.125	0.45	0.30	0.01	3130.6	2097.5	69.9
					TOTAL CO =		2.542	TOTAL NOX =		1.814	TOTAL HCX =		1.129	TOTAL CO2 =		889.2

LTO CYCLE T56 ENGINE NUMBER 8512

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1200	10000	4.000	554	27.3	15.1	1.008	1.323	0.733	0.049	12.31	6.82	0.45	3062.9	1696.9	113.1
2	1070	13500	2.000	670	12.0	8.0	0.267	7.054	4.726	0.158	2.38	1.59	0.05	3118.2	2089.2	69.6
3	1970	13800	0.500	2175	3.9	8.6	0.072	7.603	16.538	0.138	1.46	3.17	0.03	3133.7	6815.9	56.8
4	1850	13800	2.500	1870	2.4	4.5	0.187	8.688	16.247	0.677	0.36	0.68	0.03	3139.6	5871.1	244.6
5	1200	13800	4.600	860	5.7	4.9	0.376	4.787	4.117	0.316	0.38	0.33	0.03	3134.4	2695.5	206.7
6	1610	13800	0.167	1390	3.1	4.3	0.012	7.447	10.351	0.029	0.31	0.43	0.00	3138.7	4362.7	12.1
7	1200	10000	4.000	554	27.3	15.1	1.008	1.323	0.733	0.049	12.31	6.82	0.45	3062.9	1696.9	113.1
8	1070	13500	2.000	670	12.0	8.0	0.267	7.054	4.726	0.158	2.38	1.59	0.05	3118.2	2089.2	69.6
					TOTAL CO =		3.198	TOTAL NOX =		1.572	TOTAL HCX =		1.096	TOTAL CO2 =		885.8

Table 4-III. (cont)

LTO CYCLE T56 ENGINE NUMBER 8513

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1210	10000	4.000	564	26.0	14.7	0.977	3.755	2.118	0.141	12.80	7.22	0.48	3063.4	1727.8	115.2
2	1070	13500	2.000	670	5.3	3.6	0.119	3.363	2.253	0.075	0.0	0.0	0.0	3136.1	2101.2	70.0
3	1970	13800	0.500	2175	2.4	5.3	0.044	8.477	18.437	0.154	0.0	0.0	0.0	3140.7	6831.1	56.9
4	1850	13800	2.500	1870	0.0	0.0	0.0	8.859	16.567	0.690	0.0	0.0	0.0	3144.5	5880.2	245.0
5	1200	13800	4.600	860	4.8	4.1	0.318	4.892	4.207	0.323	0.08	0.07	0.01	3136.7	2697.6	206.8
6	1610	13800	0.167	1390	1.3	1.8	0.005	8.008	11.131	0.031	0.0	0.0	0.0	3142.4	4368.0	12.2
7	1210	10000	4.000	564	26.0	14.7	0.977	3.755	2.118	0.141	12.80	7.22	0.48	3063.4	1727.8	115.2
8	1070	13500	2.000	670	5.3	3.6	0.119	3.363	2.253	0.075	0.0	0.0	0.0	3136.1	2101.2	70.0
					TOTAL CO =		2.559	TOTAL NOX =		1.630	TOTAL HCX =		0.968	TOTAL CO2 =		891.4

LTO CYCLE T56 ENGINE NUMBER 8506

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1200	10000	4.000	565	27.3	15.4	1.029	20.721	11.707	0.780	12.33	6.96	0.46	3062.8	1730.5	115.4
2	1070	13500	2.000	670	12.0	8.0	0.267	10.527	7.053	0.235	2.38	1.59	0.05	3118.2	2089.2	69.6
3	1970	13800	0.500	2175	3.9	8.6	0.072	12.569	27.339	0.228	1.46	3.17	0.03	3133.7	6815.9	56.8
4	1850	13800	2.500	1870	2.4	4.5	0.187	10.459	19.634	0.818	0.36	0.68	0.03	3139.6	5871.1	244.6
5	1200	13800	4.600	860	5.7	4.9	0.376	10.380	8.927	0.684	0.38	0.33	0.03	3134.4	2695.5	206.7
6	1610	13800	0.167	1390	3.1	4.3	0.012	10.092	14.027	0.039	0.31	0.43	0.00	3138.7	4362.7	12.1
7	1200	10000	4.000	565	27.3	15.4	1.029	20.721	11.707	0.780	12.33	6.96	0.46	3062.8	1730.5	115.4
8	1070	13500	2.000	670	12.0	8.0	0.267	10.527	7.053	0.235	2.38	1.59	0.05	3118.2	2089.2	69.6
					TOTAL CO =		3.240	TOTAL NOX =		3.800	TOTAL HCX =		1.116	TOTAL CO2 =		890.2

LTO CYCLE T56 ENGINE NUMBER 8507

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1200	10000	4.000	565	27.4	15.5	1.031	3.683	2.081	0.139	14.04	7.93	0.53	3057.4	1727.4	115.2
2	1070	13500	2.000	670	3.5	2.4	0.078	7.097	4.755	0.158	0.0	0.0	0.0	3139.0	2103.1	70.1
3	1970	13800	0.500	2175	0.4	0.8	0.007	9.232	20.080	0.167	0.0	0.0	0.0	3143.9	6838.0	57.0
4	1850	13800	2.500	1870	1.3	2.5	0.104	9.678	18.098	0.754	0.0	0.0	0.0	3142.4	5876.3	244.8
5	1200	13800	4.600	860	1.1	0.9	0.070	7.581	6.519	0.500	0.0	0.0	0.0	3142.9	2702.9	207.2
6	1610	13800	0.167	1390	3.1	4.4	0.012	9.077	12.617	0.035	0.04	0.05	0.00	3139.5	4363.8	12.1
7	1200	10000	4.000	565	27.4	15.5	1.031	3.683	2.081	0.139	14.04	7.93	0.53	3057.4	1727.4	115.2
8	1070	13500	2.000	670	3.5	2.4	0.078	7.097	4.755	0.158	0.0	0.0	0.0	3139.0	2103.1	70.1
					TOTAL CO =		2.413	TOTAL NOX =		2.051	TOTAL HCX =		1.058	TOTAL CO2 =		891.7

LTO CYCLE T56 ENGINE NUMBER 8510

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1200	10000	4.000	565	27.3	15.4	1.029	17.704	10.003	0.667	12.33	6.96	0.46	3062.8	1730.5	115.4
2	1070	13500	2.000	670	12.0	8.0	0.267	6.506	4.359	0.145	2.38	1.59	0.05	3118.2	2089.2	69.6
3	1970	13800	0.500	2175	3.9	8.6	0.072	8.326	18.110	0.151	1.46	3.17	0.03	3133.7	6815.9	56.8
4	1850	13800	2.500	1870	2.4	4.5	0.187	7.866	14.710	0.613	0.36	0.68	0.03	3139.6	5871.1	244.6
5	1200	13800	4.600	860	5.7	4.9	0.376	4.414	3.796	0.291	0.38	0.33	0.03	3134.4	2695.5	206.7
6	1610	13800	0.167	1390	3.1	4.3	0.012	7.146	9.932	0.028	0.31	0.43	0.00	3138.7	4362.7	12.1
7	1200	10000	4.000	565	27.3	15.4	1.029	17.704	10.003	0.667	12.33	6.96	0.46	3062.8	1730.5	115.4
8	1070	13500	2.000	670	12.0	8.0	0.267	6.506	4.359	0.145	2.38	1.59	0.05	3118.2	2089.2	69.6
					TOTAL CO =		3.240	TOTAL NOX =		2.707	TOTAL HCX =		1.116	TOTAL CO2 =		890.2

LTO CYCLE T56 ENGINE NUMBER 8469

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1200	10000	4.000	565	27.3	15.4	1.029	2.466	1.393	0.093	12.33	6.96	0.46	3062.8	1730.5	115.4
2	1070	13500	2.000	670	12.0	8.0	0.267	3.577	2.397	0.080	2.38	1.59	0.05	3118.2	2089.2	69.6
3	1970	13800	0.500	2175	3.9	8.6	0.072	9.644	20.975	0.175	1.46	3.17	0.03	3133.7	6815.9	56.8
4	1850	13800	2.500	1870	2.4	4.5	0.187	11.186	20.917	0.872	0.36	0.68	0.03	3139.6	5871.1	244.6
5	1200	13800	4.600	860	5.7	4.9	0.376	4.922	4.233	0.325	0.38	0.33	0.03	3134.4	2695.5	206.7
6	1610	13800	0.167	1390	3.1	4.3	0.012	10.092	14.027	0.039	0.31	0.43	0.00	3138.7	4362.7	12.1
7	1200	10000	4.000	565	27.3	15.4	1.029	2.466	1.393	0.093	12.33	6.96	0.46	3062.8	1730.5	115.4
8	1070	13500	2.000	670	12.0	8.0	0.267	3.577	2.397	0.080	2.38	1.59	0.05	3118.2	2089.2	69.6
					TOTAL CO =		3.240	TOTAL NOX =		1.755	TOTAL HCX =		1.116	TOTAL CO2 =		890.2

Table 4-III. (cont)

LTC CYCLE T56 ENGINE NUMBER 8508

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1200	10000	4.000	565	27.3	15.4	1.029	23.151	13.080	0.872	12.33	6.96	0.46	3062.8	1730.5	115.4
2	1070	13500	2.000	670	12.0	8.0	0.267	8.819	5.909	0.197	2.38	1.59	0.05	3118.2	2089.2	69.6
3	1970	13800	0.500	2175	3.9	8.6	0.072	12.997	28.268	0.236	1.46	3.17	0.03	3133.7	6815.9	56.8
4	1850	13800	2.500	1870	2.4	4.5	0.187	12.382	23.155	0.965	0.36	0.68	0.03	3139.6	5871.1	244.6
5	1200	13800	4.600	860	5.7	4.9	0.376	6.021	5.178	0.397	0.38	0.33	0.03	3134.4	2695.5	206.7
6	1610	13800	0.167	1390	3.1	4.3	0.012	10.840	15.068	0.042	0.31	0.43	0.00	3138.7	4362.7	12.1
7	1200	10000	4.000	565	27.3	15.4	1.029	23.151	13.080	0.872	12.33	6.96	0.46	3062.8	1730.5	115.4
8	1070	13500	2.000	670	12.0	8.0	0.267	8.819	5.909	0.197	2.38	1.59	0.05	3118.2	2089.2	69.6
					TOTAL CO =		3.240	TOTAL NOX =		3.777	TOTAL HCX =		1.116	TOTAL CO2 =		890.2

LTO CYCLE T56 ENGINE NUMBER 8517

MODE	ITIT DEG. F	RPM	MODE TIME MINS.	FUEL LBS/ HR	*** CO *** LBS/ TPF	LBS/ HR	LBS.	*** NO2 *** LBS/ TPF	LBS/ HR	LBS.	*** HCX *** LBS/ TPF	LBS/ HR	LBS.	*** CO2 *** LBS/ TPF	LBS/ HR	LBS.
1	1140	10000	4.000	586	18.6	10.9	0.726	2.263	1.326	0.088	10.48	6.14	0.41	3082.4	1806.3	120.4
2	1070	13500	2.000	670	9.9	6.6	0.221	5.240	3.511	0.117	2.40	1.61	0.05	3121.4	2091.4	69.7
3	1970	13800	0.500	2175	1.0	2.3	0.019	7.830	17.030	0.142	0.0	0.0	0.0	3142.9	6835.8	57.0
4	1850	13800	2.500	1870	0.4	0.7	0.028	8.171	15.280	0.637	0.0	0.0	0.0	3144.0	5879.2	245.0
5	1200	13800	4.600	860	2.1	1.8	0.139	5.959	5.124	0.393	0.0	0.0	0.0	3141.2	2701.4	207.1
6	1610	13800	0.167	1390	0.5	0.8	0.002	7.559	10.506	0.029	0.0	0.0	0.0	3143.7	4369.7	12.2
7	1140	10000	4.000	586	18.6	10.9	0.726	2.263	1.326	0.088	10.48	6.14	0.41	3082.4	1806.3	120.4
8	1070	13500	2.000	670	9.9	6.6	0.221	5.240	3.511	0.117	2.40	1.61	0.05	3121.4	2091.4	69.7
					TOTAL CO =		2.081	TOTAL NOX =		1.612	TOTAL HCX =		0.926	TOTAL CO2 =		901.5

Table 4-IV.

Summary of pounds of pollutants over the LTO mission for individual T56 engines.

	Pounds pollutant			
Engine No.	CO	NO_x	HC_x	CO_2
108506*	3.24	3.80	1.12	890.2
108509	3.29	2.17	1.33	889.5
108516	3.16	1.57	1.22	887.9
108518	2.54	1.81	1.13	889.2
108512	3.20	1.57	1.10	885.8
108513	2.56	1.63	0.97	891.4
108517	2.08	1.61	0.93	901.5
108508*	3.24	3.78	1.12	890.2
108507	2.41	2.05	1.06	891.7
108510*	3.24	2.71	1.12	890.2
108469*	3.24	1.76	1.12	890.2
Mean (11)	2.93	2.22	1.11	890.7
$\pm \sigma$ (11)	0.44	0.85	0.11	3.9
Mean (7)	2.75	1.77	1.11	N/A
$\pm \sigma$ (7)	0.47	0.25	0.14	N/A

*Based on Engine 108512 regression (see text).

Listed in Table 4-V are the pounds of pollutants per one thousand pounds of fuel for each pollutant for each engine.

Table 4-VI is a summary of pounds of pollutants per minute and pounds of pollutants per pound of fuel in each mode, averaged over all eleven engines. As in other tables, the data for Table 4-VI were taken from Table 4-III.

Table 4-V.
Summary of pounds of pollutants per thousand pounds of fuel over the LTO mission for individual T56 engines.

Engine No.	Pounds pollutant/1000 lb fuel			
	CO	NO_x	HC_x	Total
108506*	11.4	13.3	3.9	28.6
108509	11.5	7.6	4.6	23.7
108516	11.1	5.5	4.3	20.9
108518	8.9	6.4	4.0	19.3
108512	11.2	5.5	3.8	20.5
108513	9.0	5.7	3.4	18.1
108517	7.3	5.7	3.3	16.3
108508*	11.4	13.2	3.9	28.5
108507	8.5	7.2	3.7	19.4
108510*	11.4	9.5	3.9	24.8
108469*	11.4	6.2	3.9	21.5
Mean	10.3	7.8	3.9	22.0
Mean % of total	46.8	5.5	17.7	100.0
$\pm\sigma$	1.5	2.9	0.4	4.0
$\pm\sigma$ % of mean	14.5	37.0	10.3	---

*Based on Engine 108512 regression (see text).

Sampling Quality

It was necessary to provide representative means to sample the T56 exhaust gas. The sampling probe and lines have been discussed previously but here evidence is presented based on a carbon balance which indicates that sampling was very representative and that analytical results are consistent. For example, consider the data from Engine 108516 as reported in Table 4-III. The theoretical value of pounds of CO_2 per 1000 pounds of fuel (H/C ratio = 1.97) is given by

$$\frac{1000 \times 44.011}{12.011 + 1.97 \times 1.008} = 3144.4.$$

Table 4-VI.

Rate of formation of pollutants averaged over all engines for each mode of the LTO cycle.

Mode		Pounds pollutant/min × 100			Pounds pollutant/pound of fuel		
No.	Description	CO	NO_x	HC_x	CO	NO_x	HC_x
1	LSGI	25.3	7.2	12.2	26.9	7.6	13.0
2	GI	11.2	7.2	2.1	10.0	6.4	1.9
3	TO	10.8	33.2	3.4	2.9	9.6	0.9
4	Climb	4.9	29.8	0.7	1.6	9.6	0.2
5	Approach	5.9	8.9	0.4	4.1	6.2	0.2
6	Reverse	5.1	19.8	0.0	2.2	8.6	0.2
7	LSGI	25.3	7.2	12.2	26.9	7.6	13.0
8	GI	11.2	7.2	2.1	10.0	6.4	1.9

Table 4-VII shows the final corrected values of pounds of CO, HC_x, and CO_2 per thousand pounds of fuel, together with computed values of CO_2 after converting measured CO to CO_2 and measured HC_x to CO_2. The CO and HC_x values are converted to equivalent CO_2 by

$$CO \times \frac{44.011}{28.01} = \text{equivalent } CO_2 \text{ from CO}$$

$$HC_x \times \frac{44.011}{13.981} = \text{equivalent } CO_2 \text{ from } HC_x$$

Table 4-VII.

Carbon balance results from Engine 108516 in LTO cycle.

(Concentrations are pounds pollutant/1000 lb fuel)

Mode	CO	HC_x	CO_2	Total CO_2
1	29.0	14.9	3052.1	3144.6
2	9.9	1.23	3125.1	3144.5
3	5.3	11.92	3130.2	3144.6
4	1.4	0.22	3141.6	3144.5
5	5.1	0.02	3136.4	3144.5
6	1.5	0.15	3141.7	3144.5
7	29.0	14.9	3052.1	3144.6
8	9.9	1.23	3125.1	3144.5

Considering the fact that CO, HC_x, and CO_2 are measured on independently calibrated analyzers and the total CO_2 values of Table 4-VII are so close to the theoretical value of 3144.4, it was concluded that the sampling was representative and the analyses are good. Moreover, the regression equations provide very good interpolations, at least in this case.

Smoke Index* Correlations

A careful examination of the raw smoke index measurements shows that the span of index values for Engines 108506, 108508, 108510, and 108469 is so small as to render them essentially constant and thus show poor correlation against the independent variables. When these engines are removed from the sample, all the remaining engines have high R^2 values and, except for Engines 108509 and 108516, smoke index correlates well with 1/HP by a regression equation of the form:

$$SMOK = a - b/HP$$

Figure 4-3 illustrates this behavior for Engine 108518. Note the S(y) bands on either side of the regression line. It would be highly desirable to have more low-power smoke index values.

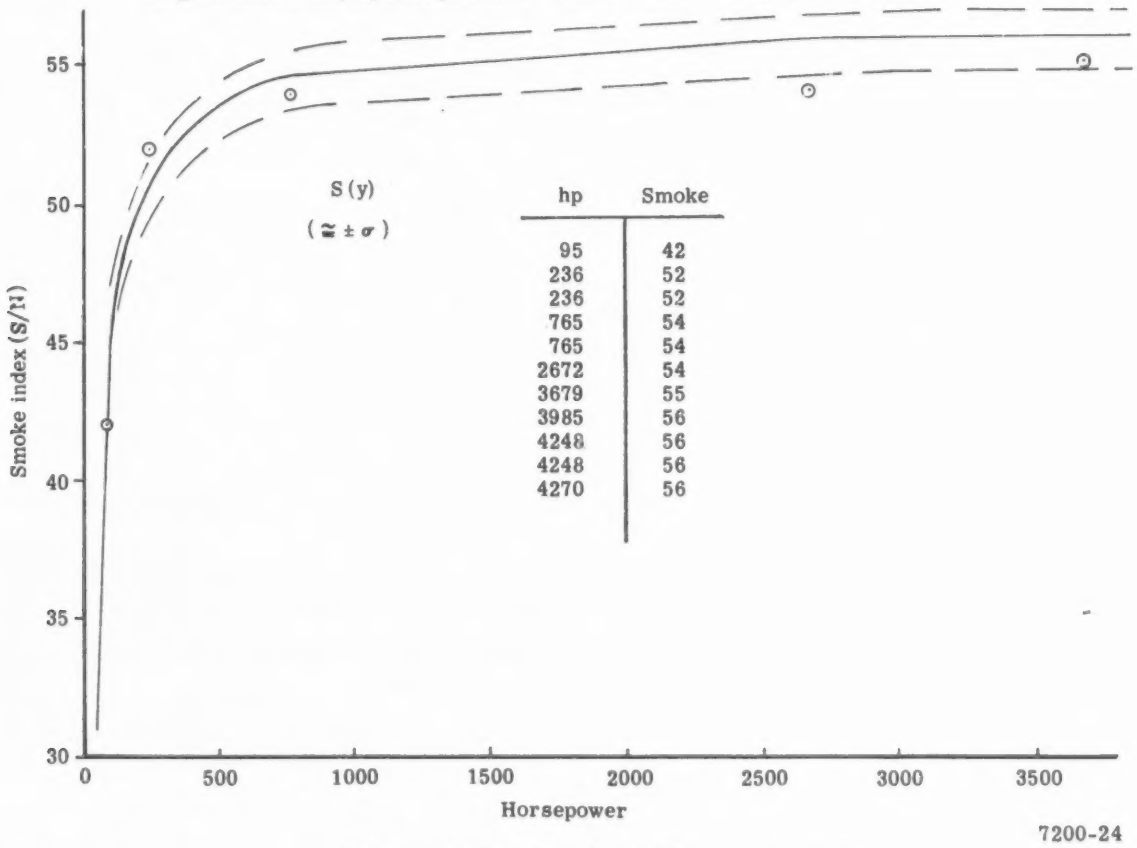

Figure 4-3. Smoke index vs power.

*Or Smoke number (S/N)

Aldehyde Measurements

Aldehydes were measured by a wet chemical method for each setting of Engine 108517. All observations were at the limit of detection of the method—viz, less than 1.0 ppm formaldehyde—except the value at ground start which was 3.0 ppm. No statistical observations are possible.

Particulates

The particulate values reported in Section III were used to compute the particulate emission index which is given in Table 4-VIII. No statistical analysis was possible because of the small number of data points.

Table 4-VIII.
Particulate emission rates.

(LACAPCD impingers—JP-5 fuel)

LTO mode	Power setting	Particulates (lb/1000 lb fuel)
1	LSGI	18.1
2	GI	21.7
3	TO	5.34
4	Climb	8.96
5	Approach	16.3
6	Reverse	10.7
7	LSGI	18.1
8	GI	21.7

COMMENTARY

Variability of Results

The variability of the mass emissions was computed for the LTO mission (Table 4-IV) for the eleven engines tested. Expressed in percent of total mass for the entire LTO, these are:

Pollutant	CO	NO_x	HC_x	CO_2
Mean wt, lb	2.93	2.22	1.11	890.7
$\pm\sigma$, lb	0.44	0.85	0.11	3.9
$\pm\sigma$ as percent of mean wt	15.0	38.0	10.0	0.43

Three known sources contribute to this variability, none of which could be evaluated separately during this series of tests:

- Measurement error
- Engine variations
- Analytical variance

The general performance of the measurement system and problems contributing to measurement error are discussed in Section III. The largest data scatter occurred at low concentration levels. It is expected that the contribution to variability of these points might be considerable.

True performance variations existed over the eleven engines tested and are illustrated by the variability in brake specific fuel consumption of the engines tested for emissions:

Avg BSFC = 0.5044
Lowest BSFC = 0.4950
Highest BSFC = 0.5110

All of the preceding data were corrected to standard inlet conditions.

Emissions performance variations also undoubtedly exist but could not be evaluated statistically with the small number of engines sampled. Improved measurement accuracy, good statistical knowledge of that accuracy, and an adequate sample size are required before a finite value of engine-to-engine variation can be obtained.

The emission tests in this program were run over a production test cycle. Conversion of these data to the LTO emissions test cycle required interpolation of data which was done with regression techniques to minimize interpolation error. Nevertheless, until the emissions test cycles are run directly, some error in converting data will occur.

LTO Cycle

The use of a landing-takeoff operational cycle as a means to evaluate the emissions from aircraft engines could impose large bias values, depending on the time assumed for each operational mode. The influence of time in mode and emission rates is illustrated in Figure 4-4. In this chart, the mean rates of mass emissions are represented by the bar height and the time in mode by the bar width. The area is the mass emissions in the mode. The extreme influence of the long holding times on total emissions is clearly shown by the large area of the CO and HC_x bars at LSGI. The higher power settings of TO and Climb have a similar influence on the mass of NO emissions:

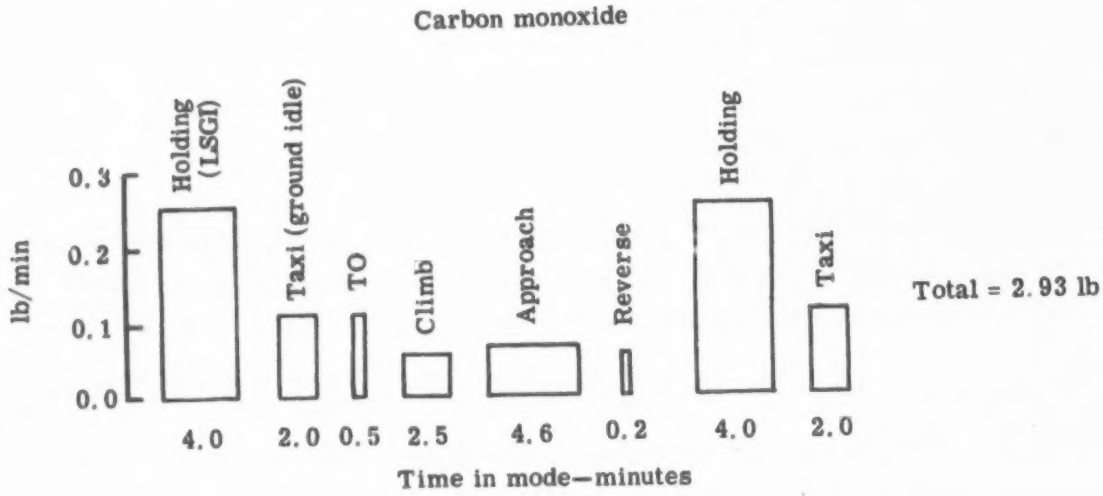

Figure 4-4. Average LTO emissions.

LSGI = 69% of all CO mass
LSGI = 88% of all HC_X mass
TO and Climb = 41% of all NO mass

Importance of Transients

Emissions during acceleration, deceleration, and starting transients were measured. Each recorded transient was integrated to find an average concentration level from which the mass values were computed. Table 4-IX contains a comparison of the mass values obtained from transient measurements and those of the total LTO. From this, it is obvious that transients represent only a very insignificant portion of the total mass emissions except during engine starts.

Table 4-IX.
Mass emissions during transients.

(T56-A-15 Engine 108518)

Running transients	Pollutant	lb/transient	% of total LTO emissions
Low speed ground idle	CO	0.19	6.6
to ground idle	HC_X	0.058	5.2
Flight idle to takeoff	CO	0.56	1.6
	HC_X	No change	---
	NO	0.137	6.2
Takeoff to flight idle	CO	0.068	2.4
	HC_X	No change	---
	NO	0.095	4.3
Starting transients			
Ambient	CO	0.91	31
	HC_X	0.45	41
	NO	0.036	1.6
Hot start No. 1	CO	0.86	30
	HC_X	0.28	25
	NO	0.036	1.5
Hot start No. 2	CO	0.95	33
	HC_X	0.51	47
	NO	0.048	2.2

V. CONCLUSIONS AND RECOMMENDATIONS

Emissions were measured satisfactorily on the eleven production engines; the average emission levels and variations were determined over the operating range of each. However, the variations could not be specifically proportioned among true engine variation, instrument variability, and variation incurred by measuring a production test cycle and converting to the emission cycle. True engine variability and instrument variability should be assessed by a test which includes a larger number of engines (samples) and by a statistically planned evaluation of instrument error.

Emissions during engine transients were found to be very low—about one twentieth of the total LTO mass emissions.

Unburned hydrocarbons and carbon monoxide transient emissions during engine start (measured on one engine) were high. They amounted to nearly one third of the HC_x and CO mass emitted during the LTO cycle. Additional testing to verify these values over a larger sample of engines is recommended.

In general, all measurements taken were satisfactory except the lowest levels of hydrocarbons and oxides of nitrogen where test stand background (HC_x) and instrument noise (NO) detracted from the quality of the measurements. The development of measurement technology should be emphasized until very low concentration measurements can be made accurately and routinely.

Operation of the chemiluminescent NO-NO_2 instrument was excellent. Instrument response to engine transients was much better than that of a long-path infrared instrument. Continued application of the instrument in gas turbine emission measurements is recommended.

The theory behind the special 28-hole gas sampling probe used for these tests was proved. This probe obtained a representative sample of the engine exhaust gases.

The landing-takeoff (LTO) emission test cycle used for the analysis was developed from a study of Model T56 engine-powered aircraft. It showed that LTO total mass emissions were highly sensitive to the length of time the aircraft was held stationary during ground operations. Because of the degree of its influence on total mass emissions, aircraft handling and all of its variabilities should be divorced from engine emission test cycles.

VI. REFERENCES

1. Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines. Society of Automotive Engineers, Aeronautical Recommended Practice ARP1256 (Final Draft). 25 May 1971.

2. Aircraft Gas Turbine Engine Exhaust Smoke Measurement. Society of Automotive Engineers, Aeronautical Recommended Practice ARP1179. 4 May 1970.

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5. Efroymson, M. S. "Multiple Regression Analysis," in Mathematical Methods for Digital Computers, Anthony Ralston and Herbert S. Wilf, ed. (John Wiley and Sons, 1960) Section 17.

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APPENDIX A

Description of Measurement Methods

HYDROCARBON ANALYZER

The Flame Ionization Detector (FID) is an on-line, portable unit containing a Beckman GC-4 burner and a Kiethly electrometer. The FID can be used for altitude engine testing and high-pressure rig applications. It incorporates a remotely operated burner detector and high-temperature valving which ensures accurate flow control. The FID operates on the principle of hydrogen flame ionization of carbon atoms. This unit was built from designs originating at the U.S. Bureau of Mines, American Oil Research, and Detroit Diesel Allison. It was placed in service at Detroit Diesel Allison in December 1970.

Specifications

Sensitivity	Approximately 1 ppm at a concentration of 100 ppm and attenuation of 10,000X. Response is essentially linear.
Range	Parts per billion to 100% concentration.
Attenuation	1, 2, 4, 8, 16, 32, 64, 128 on electrometer; steps of 10X on preamp.
Stability	Stabilized electronics are drift free.
Reproducibility	±1.0% with successive identical samples.
Readout	L&N Speedomax recorder, 2 in./min.
Sample Requirements	0 to 0.5 ft^3/min exhaust bypass rate. 1 to 10 cc/min sample flow rate to burner, 5 in. Hg vacuum in burner vessel induces sample flow of approximately 10 cc/min.

INFRARED GAS ANALYZERS

The Model 200 Luft-type infrared analyzer (LIRA), manufactured by Mine Safety Appliances Company, was used to measure CO, CO_2, and NO. Four instruments were assembled into a cart which contained flow regulators, flow meters, pressure and temperature gages, and other equipment necessary to measure and maintain sample and calibrating gas flows to each instrument.

Instrument Ranges

CO 0-100, 0-1000 ppm
CO_2 0-1.5, 0-15%
NO 0-300, 0-1000, 0-3000 ppm

Accuracy

Rated at 1% of scale.

NO-NO_x ANALYZER

The Thermo Electron (TECO) Model 10A chemiluminescent analyzer was used to measure NO and NO_x in the gas turbine exhaust. The chemiluminescent reaction of NO and ozone is the basis of operation of the TECO instrument.

Specifications

Sensitivity	2.5, 10, 25, 100, 250, 1000, 2500, and 10,000 ppm full scale.
Selectivity	Selective detection of NO with negligible interference from water vapor or other constituents in typical emission samples.
Response	Less than one second with continuous monitoring; also linear response on all ranges and from range to range.
Stability	Excellent.

SMOKE

A Bacharach smokemeter, Model RDC, was modified to comply with the SAE ARP1179 sampling technique. This is a spot filtration sampling method with a controlled sampling volume and uses a photometer to grade the stained disks. Filter material is Whatman No. 4.

ALDEHYDES

The MBTH method was employed to identify aldehydes. Gas samples are collected in evacuated bottles through a heated sample line. The bottles contain a dilute solution of 3-methyl-2-benzothiazolone hydrazone hydrochloride—hence MBTH. A wet chemical analysis follows. This method covers a range from 0 to 200 ppm.

SALTZMAN

The modified Saltzman technique wet-chemical procedure was developed originally as a colorimetric microdetermination of the concentrations of nitrogen dioxide (NO_2) in the atmosphere. It has been adapted to exhaust gas measurements by allowing the complete oxidation of nitric oxide (NO) to NO_2 prior to analysis. The standard Saltzman reagent is used, and results are analyzed on a Beckman Model B spectrophotometer.

APPENDIX B

Emissions Data Tables.

PTS INITIAL RUN SET POINT DEFINITION

Set points	Engine power
1, 17	Low speed ground idle
2, 18	Ground idle
3	75% normal
4	100% normal
5	Military
6, 10, 14	Takeoff
7, 11	Decel
8, 12	Flight idle
9, 13	Accel
15	Reverse
16, 19	Shutdown

PTS FINAL RUN SET POINT DEFINITION

Set points	Engine power
1, 14	Low speed ground idle
2	75% normal
3	100% normal
4	Military
5, 9	Takeoff
6	Reverse
7, 11	Flight idle
8, 13	Accel
10	Decel
12, 16	Shutdown
15	Ground idle

Engine	Set	Speed (rpm)	Fuel flow (lb/hr)	Torque (in.-lb)	Turbine inlet temp (°F)	Compr inlet temp (°F)	Rel humid. (%)	LIRA CO (ppm vol)	LIRA CO_2 (% vol)100	LIRA NO (ppm vol)	FID HC_x (ppm vol)	Smoke NO	Barom press. (in.Hg)	CHO (ppm vol)	Saltz (ppm vol)	CI NO_2 (ppm vol)	CI NO + NO_2 (ppm vol)
108518-I	2	13500	731	1100	1065	87	50	59	155	40	3	52	28.7	---	---	---	---
	3	13800	1589	12200	1610	90	45	34	343	68	3	54	28.9	---	---	---	---
	4	13800	1980	16800	1850	91	44	34	432	114	15	55	28.9	---	---	---	---
	5	13800	2118	18200	1920	91	44	36	453	---	14	---	29.0	---	---	---	---
	10	13800	2260	19500	1970	91	44	50	470	118	10	---	29.0	---	---	---	---
	12	13400	890	3600	1165	86	52	54	218	40	10	54	28.9	---	---	---	---
	6	13800	2241	19400	1970	91	44	39	470	114	15	56	29.0	---	---	---	---
	8	13400	889	3600	1165	87	50	54	215	38	10	---	28.9	---	---	---	---
	4	13800	2258	19400	1970	90	45	39	470	112	5	---	29.0	---	---	---	---
	17	---	---	---	---	---	52	355	270	30	390	42	---	---	---	---	---
	18	13500	742	1100	1050	83	58	---	155	14	3	---	28.8	---	---	---	---
108512-I	2	13500	714	1100	1040	90	49	66	135	37	3	---	28.6	---	---	---	---
	3	13800	1530	11600	1610	98	38	34	303	91	3	54	28.9	---	---	---	---
	4	13800	1900	16000	1850	100	35	32	368	138	3	---	29.0	---	---	---	---
	18	13500	712	1100	1080	97	39	---	155	18	3	---	28.9	---	---	---	---
	10	13800	2110	18200	1970	102	34	41	435	106	3	---	29.0	---	---	---	---
	12	13400	881	3800	1205	97	39	57	200	32	3	55	28.9	---	---	---	---
	6	13800	2110	18200	1970	102	34	39	415	130	3	---	29.0	---	---	---	---
	8	13400	872	3700	1205	97	39	55	200	42	3	---	28.9	---	---	---	---
	14	13800	2110	18200	1970	102	34	39	435	88	3	57	29.0	---	---	---	---
	17	10000	554	600	1200	98	38	380	265	18	331	---	28.9	---	---	---	---
108513-I	2	13500	708	1000	1070	96	44	55	159	21	3	52	28.8	---	34	---	---
	3	13800	1490	11000	1610	100	39	40	309	66	3	53	28.7	---	89	---	---
	4	13800	1862	15400	1850	102	37	35	405	89	3	56	28.7	---	126	---	---
	5	13800	1977	16700	1970	102	37	36	426	132	22	55	28.7	---	---	---	---
	10	13800	2074	17600	1970	102	37	40	441	139	10	55	28.7	---	---	---	---
	12	13400	896	3900	1230	99	40	51	208	31	18	56	28.8	---	---	---	---
	6	13800	2072	17600	1970	103	36	39	444	123	19	---	28.7	---	139	---	---
	8	13400	902	3900	1235	99	40	51	208	37	12	---	28.7	---	51	---	---
	17	10000	564	400	1210	97	43	375	277	23	350	---	28.7	---	35	---	---
	18	13500	711	1000	1070	97	43	30	160	28	3	---	28.5	---	---	---	---
108517-I	2	13500	726	1100	1070	86	48	54	140	24	3	51	28.9	1	---	20	26
	3	13800	1570	11600	1610	94	37	34	298	68	3	58	29.0	1	---	68	73
	4	13800	1950	16200	1850	96	34	32	423	107	3	56	29.0	1	---	100	107
	5	13800	2065	17400	1920	98	32	30	479	114	3	---	29.0	---	---	107	114
	10	13800	2150	18400	1970	99	30	32	498	107	3	---	29.0	1	---	115	120
	12	13400	892	3800	1200	94	37	46	235	32	3	---	28.9	1	---	31	38
	6	13800	2150	18400	1970	99	30	30	493	111	3	56	29.0	---	---	107	115
	8	13400	896	3900	1200	94	37	46	230	34	3	54	28.9	---	---	33	38
	14	13800	2150	18400	1970	99	30	29	490	102	3	---	29.0	1	---	111	118
	17	10000	586	---	1140	94	37	320	318	20	350	---	28.9	3	---	17	25
	18	13500	1100	---	1075	94	37	---	188	38	3	---	28.9	---	---	22	28
108508-F	1	13500	732	1200	1075	79	43	55	135	29	---	56	28.8	---	---	---	---
	2	13800	1572	12200	1610	80	42	32	312	94	---	60	29.0	---	---	---	---
	3	13800	1980	17600	1850	86	35	34	366	126	10	60	29.0	---	---	---	---
	5	13800	2190	19400	1970	88	32	35	419	160	10	58	29.0	---	---	---	---
	6	14300	1080	5100	1375	115	15	35	250	76	30	59	28.9	---	---	---	---
	7	13400	916	3700	1220	88	32	49	203	42	10	58	28.9	---	---	---	---

Engine	Set	Speed (rpm)	Fuel flow (lb/hr)	Torque (in.-lb)	Turbine inlet temp (°F)	Compr inlet temp (°F)	Rel humid. (%)	LIRA CO (ppm vol)	LIRA CO_2 (% vol)100	LIRA NO (ppm vol)	FID HC_x (ppm vol)	Smoke NO	Barom press. (in.Hg)	CHO (ppm vol)	Saltz (ppm vol)	CI NO_2 (ppm vol)	CI $NO + NO_2$ (ppm vol)
108507-F	1	13500	720	1100	1075	82	38	60	214	32	45	52	28.7	---	---	---	---
	2	13800	1550	11600	1610	89	30	34	336	82	3	56	28.9	---	---	---	---
	3	13800	1950	16400	1850	91	28	36	427	120	3	57	28.9	---	---	---	---
	4	13800	2080	17700	1920	93	27	37	427	108	3	58	28.9	---	---	---	---
	5	13800	2170	18800	1970	94	26	40	449	132	3	55	28.9	---	---	---	---
	7	13400	910	3900	1225	91	28	54	214	51	3	---	28.9	---	---	---	---
	9	13800	2170	18800	1970	94	26	42	461	150	---	---	28.9	---	---	---	---
	11	13400	908	3900	1220	91	28	---	---	---	---	54	28.9	---	---	---	---
	14	10000	576	600	1205	89	30	390	283	32	400	43	28.9	---	---	---	---
	15	13500	720	1100	1090	89	30	67	175	34	3	---	28.7	---	---	---	---
108506-F	1	13500	721	1100	1090	90	30	---	142	32	40	62	28.8	---	---	---	---
	2	13800	1522	10700	1610	92	29	30	323	97	13	59	28.9	---	---	---	---
	3	13800	1925	16400	1850	93	28	32	410	129	2	60	28.9	---	---	---	---
	5	13800	2152	19000	1970	93	28	34	443	152	2	60	28.9	---	---	---	---
	6	14200	1058	4800	1385	127	10	35	---	129	3	57	28.8	---	---	---	---
	7	13400	900	3900	1175	95	26	---	---	71	3	62	28.9	---	---	---	---
	15	13500	730	1200	1085	88	32	50	---	30	23	---	28.7	---	---	---	---
108509-F	1	13500	718	1100	990	90	29	52	170	46	32	52	28.7	---	---	---	---
	2	13800	1544	11600	1610	92	28	37	346	102	5	53	28.8	---	---	---	---
	3	13800	1940	16400	1850	93	27	37	442	142	3	53	28.8	---	---	---	---
	4	13800	2045	17600	1920	93	27	35	455	145	---	---	28.9	---	---	---	---
	5	13800	2128	19800	1970	94	26	35	470	150	3	53	28.9	---	---	---	---
	7	13400	908	3900	1250	95	26	37	218	32	8	54	28.8	---	---	---	---
	9	13800	2150	18800	1970	95	25	35	490	150	3	---	28.9	---	---	---	---
	14	10000	572	600	1205	91	29	450	---	29	380	41	28.8	---	---	---	---
108516-I	2	13400	714	10	1070	82	47	63	151	24	7	50	28.8	---	---	---	---
	3	13800	1575	119	1610	77	56	34	330	88	3	56	29.0	---	---	---	---
	4	13800	1970	168	1850	80	50	36	410	115	3	58	29.0	---	---	---	---
	18	13500	753	12	1075	78	54	---	151	24	---	---	28.9	---	---	---	---
	10	13800	2190	197	1970	81	49	43	440	164	3	---	29.1	---	---	---	---
	12	13400	896	38	1195	79	52	58	210	42	3	---	29.0	---	---	---	---
	6	13800	2175	192	1970	81	49	40	440	138	3	56	29.1	---	---	---	---
	8	13400	900	38	1195	78	54	57	205	28	3	54	29.0	---	---	---	---
	17	10000	---	---	---	---	54	375	250	6	370	42	---	---	---	---	---
108510-F	1	13500	720	1100	1055	76	60	49	163	31	---	53	28.6	---	---	---	---
	2	13800	1570	12400	1610	80	55	34	352	74	---	57	28.8	---	---	---	---
	3	13800	2000	17400	1850	83	49	35	445	102	---	60	28.8	---	---	---	---
	5	13800	2210	19800	1970	85	46	38	438	100	---	58	28.9	---	---	---	---
	6	14300	1041	4900	1365	112	20	33	313	82	---	58	28.8	---	---	---	---
	7	13400	899	4100	1210	84	46	52	222	31	---	57	28.8	---	---	---	---
108469-F	1	13500	732	1200	1105	89	34	55	155	---	15	50	28.8	---	---	---	---
	2	13800	1512	11400	1610	91	32	32	328	108	9	52	28.9	---	---	---	---
	3	13800	1925	16100	1850	92	31	34	410	129	3	54	29.0	---	---	---	---
	4	13800	2020	17100	1920	93	30	32	465	129	---	---	29.0	---	---	---	---
	5	13800	2090	17900	1970	94	29	35	471	153	4	54	29.0	---	---	---	---
	6	14300	1040	4300	1410	130	10	35	---	77	3	53	28.9	---	---	---	---
	7	13400	918	4000	1255	94	29	49	213	42	---	52	28.9	---	---	---	---
	9	13800	2100	17900	1970	93	30	38	442	---	---	---	29.0	---	---	---	---

I = initial run set points

F = final run set points

APPENDIX C

Computation Methods from ARP1256

The following computations of mass concentrations from volume concentration and dry to wet conversions are outlined in the preliminary draft of SAE ARP1256, Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines (May 25, 1971):

DEFINITION OF TERMS

- CO = concentration of CO in exhaust, ppm
- CO_2 = concentration of CO_2 in exhaust, %
- C = concentration of hydrocarbon (HC) in exhaust, ppm C
- NO = concentration of NO in exhaust, ppm
- NO_2 = concentration of NO_2 in exhaust, ppm
- F = mass rate of fuel usage, lb/hr
- w_X = mass emission rate of component X, lb/hr
- W_X = mass emission rate of component X, lb/1000 lb fuel
- M_C = atomic weight of carbon
- M_H = atomic weight of hydrogen
- a = (atomic) hydrogen/carbon ratio of fuel
- a = 2 in approximation equations

EQUATIONS FOR CALCULATING WEIGHT OF EMISSIONS

These equations use fuel consumption data and emission concentration values based on wet (or actual) exhaust measurement. Note that for all this computation, the concentration values for all species must be on the same basis—that is, either all on an actual or all on a dry basis.

$$w_{CO} = \frac{M_{CO}\,\frac{CO}{10^4}\,F}{(M_C + a\,M_H)\left(\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}\right)} \approx \frac{2\,\frac{CO}{10^4}\,F}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

$$w_{HC} = \frac{\frac{C}{10^4}\,F}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

$$W_{NO\ (as\ NO_2)} = \frac{M_{NO_2}\ \frac{NO}{10^4}\ F}{(M_C + a\,M_H)\left(\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}\right)} \approx \frac{3.29\ \frac{NO}{10^4}\ F}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

$$W_{CO} = \frac{2.801\ (CO)}{(M_C + a\,M_H)\left(\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}\right)} \approx 0.20\ \frac{(CO)}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

$$W_{HC} = \frac{0.100\ (C)}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

$$W_{NO\ (as\ NO_2)} = \frac{4.601\ (NO)}{(M_C + a\,M_H)\left(\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}\right)} \approx \frac{0.329\ (NO)}{\frac{CO}{10^4} + CO_2 + \frac{C}{10^4}}$$

CONVERSION OF CONCENTRATIONS (DRY) TO WET BASIS

Concentration (wet basis) = K • concentration (dry basis)

y = water content of intake air (% by volume)

For the case in which all measurements were determined on a dry basis:

Correcting only for water of combustion:

$$K_d = \frac{100}{100 + \frac{a}{2}\left(\frac{CO}{10^4} + CO_2\right)}$$

Correcting for water of combustion and water vapor in intake air:

$$K_w = K_d\ \frac{200 - y\left(1 + \frac{a}{2}\right)}{200 - y + \frac{K_d\ y\ a}{2}\left(1 - \frac{CO}{10^6}\right)}$$

The water content of the intake air, y, was computed from measured quantities using the equation

$$y = \frac{iHUM}{14.7} \times \exp\left(16.8545 - \frac{9476.4}{459.7 + iCIT}\right) \text{percent water by volume.}$$

The exponential term in the preceding equation arises from an Antoine equation fit to water vapor pressure data.

APPENDIX D

Airflow at Various Values of Compressor Inlet Pressure and Temperature

Pressure (in. Hg)	Temperature (°F)								
	20	30	40	50	60	70	80	90	100
28.5	34.33	33.69	33.00	32.31	31.63	30.93	30.22	29.52	28.81
28.6	34.45	33.80	33.11	32.43	31.74	31.04	30.32	29.62	28.91
28.7	34.57	33.92	33.23	32.54	31.85	31.15	30.43	29.73	29.01
28.8	34.69	34.04	33.34	32.65	31.96	31.26	30.53	29.83	29.11
28.9	34.81	34.16	33.46	32.77	32.07	31.37	30.64	29.93	29.21
29.0	34.93	34.27	33.58	32.88	32.18	31.47	30.75	30.04	29.31
29.1	35.05	34.39	33.69	32.99	32.29	31.58	30.85	30.14	29.41
29.2	35.17	34.51	33.81	33.10	32.40	31.69	30.96	30.25	29.51
29.3	35.29	34.63	33.92	33.22	32.51	31.80	31.06	30.35	29.61
29.4	35.41	34.75	34.04	33.33	32.62	31.91	31.17	30.45	29.72
29.5	35.53	34.86	34.15	33.44	32.73	32.01	31.27	30.55	29.82
29.6	35.66	34.98	34.27	33.56	32.85	32.12	31.38	30.66	29.92
29.7	35.77	35.10	34.38	33.67	32.96	32.23	31.49	30.76	30.02
29.8	35.89	35.22	34.50	33.78	33.06	32.34	31.59	30.86	30.12
29.9	36.04	35.36	34.64	33.92	33.20	32.47	31.72	30.99	30.24
30.0	36.14	35.46	34.73	34.01	33.29	32.56	31.81	31.07	30.32

APPENDIX E

Tables of Analytical Results

Engine	Component	Regression coefficients A_1	A_2	A_3	A_4	A_5	S(y)	R^2	N
108506	CO	-163.57	0	27413.03	-0.0879	16161.9	18.33	0.978	7*
	HC_x	-241.88	0	30579.1	-0.09168	16444.1	25.58	0.959	7*
	NO_x	86.108	-0.1995	21174.8	0	3959.9	5.44	0.993	7
	CO_2	0.00635	0.00006943	191.159	0	-4.3363	0.00204	0.999998	7*
	Smoke	59.182	0	0	0	689.01	1.61	0.395	7
108509	CO	-674.1	0.61453	0	-0.12159	35570.6	14.302	0.994	8
	HC_x	-600.19	0.522	0	-0.10304	34180.8	12.453	0.995	8
	NO_x	24.9739	0	0	0.028306	0	9.851	0.969	8
	CO_2	0.13116	-0.0000777	198.701	0.00001033	-7.8736	0.00235	0.999998	8
	Smoke	69.0386	-0.012385	0	0.002025	-1261.7	0.4604	0.993	8
108516	CO	380.12	-0.71809	51044.2	0	18869.5	10.51	0.994	9
	HC_x	-371.91	0	47309.8	-0.1453	16415.1	11.54	0.994	9
	NO_x	836.82	-0.9137	11760.7	0.20119	7905.29	6.720	0.992	9
	CO_2	0.005525	0.00008229	191.27	0	-5.2095	0.00304	0.999995	9
	Smoke	54.883	0	99.764	0	-1333.63	0.8109	0.980	9
108518	CO	-204.91	0	30618.7	-0.10388	14000.9	7.802	0.995	11
	HC_x	-368.56	0	46051.8	-0.1519	15413.4	8.893	0.996	11
	NO_x	-73.497	0.092716	0	0	0	8.0847	0.961	11
	CO_2	0.01949	0.00006518	191.55	0	-5.2703	0.00194	0.999998	11
	Smoke	55.9905	0	0	0	-1245.21	0.9172	0.954	11
108512	CO	-163.57	0	27413.03	-0.0879	16161.9	18.33	0.978	10
	HC_x	-241.88	0	30579.1	-0.09168	16444.1	25.58	0.959	10
	NO_x	60.275	0	-8131.6	0.05349	4819.5	16.85	0.898	10
	CO_2	0.00635	0.00006943	191.159	0	-4.3363	0.00204	0.999998	10
	Smoke	99.2853	-0.054412	1777.08	0.007229	-1389.50	0.9276	0.976	10
108513	CO	-254.7	0	43154	-0.15786	1938.6	18.74	0.977	10
	HC_x	-761.98	0.4948	38783.1	-0.26266	0	14.67	0.988	10
	NO_x	-102.64	0.11032	0	0	0	11.42	0.942	10
	CO_2	0.07827	0	189.97	0.00002149	-1.4863	0.00179	0.999998	10
	Smoke	75.8797	-0.030094	1865.48	0	-1311.26	0.7716	0.970	10
	Saltz	-32.52078	0.0568627	0	0.015793	0	4.5497	0.993	10
108517	CO	-80.58	0	10516.2	-0.03277	19789.2	24.275	0.937	11
	HC_x	-177.10	0	14821.3	-0.03924	26218.9	36.226	0.916	11
	NO_x	19.271	0	0	0.02076	0	7.0974	0.967	11
	CO_2	0.05841	0	196.03	0	-5.7919	0.00327	0.999994	11
	Smoke	56.6963	0	0	0	-1369.55	0.92873	0.961	11
	NO_2	9.49107	0	457.802	0.022492	0	3.2075	0.995	11
	$NO + NO_2$	13.348	0	728.952	0.021653	0	3.0354	0.996	11

*Based on Engine 108512 regression (see page 4-7).

Tables of Analytical Results (cont)

Engine	Component	Regression coefficients A_1	A_2	A_3	A_4	A_5	S(y)	R^2	N
108508	CO	-163.57	0	27413.03	-0.0879	16161.9	18.33	0.978	6*
	HC_x	-241.88	0	30579.1	-0.09168	16444.1	25.58	0.959	6*
	NO_x	-264.3	0.1888	8794.2	-0.03136	10378.6	0.7390	0.99995	6
	CO_2	0.00635	0.00006943	191.159	0	-4.3363	0.00204	0.999998	6*
	Smoke	59.563	0	0	0	-924.75	0.87872	0.731	6
108507	CO	-1694.9	1.6268	8443.8	-0.4029	2856.4	5.664	0.998	10
	HC_x	-1794.1	1.5428	27165.3	0.4439	0	8.978	0.996	10
	NO_x	27.149	0	0	0.02357	0	9.1157	0.959	10
	CO_2	0.0654	0	196.76	0	-6.944	0.005887	0.99998	10
	Smoke	56.4114	0	0	0	-1232.1	1.132	0.935	10
108510	CO	-163.57	0	27413.03	-0.0879	16161.9	18.33	0.978	6*
	HC_x	-241.88	0	30579.1	-0.09168	16444.1	25.58	0.959	6*
	NO_x	-226.45	0.1698	7306.4	-0.03863	6702.98	3.224	0.998	6
	CO_2	0.00635	0.00006943	191.159	0	-4.3363	0.00204	0.999998	6*
	Smoke	58.799	0	0	0	-1369.2	1.070	0.829	6
108469	CO	-163.57	0	27413.03	-0.0879	16161.9	18.33	0.978	8*
	HC_x	-241.88	0	30579.1	-0.09168	16444.1	25.58	0.959	8*
	NO_x	-276.12	0.3312	-7708.5	-0.01717	0	7.273	0.985	8
	CO_2	0.00635	0.00006943	191.159	0	-4.3363	0.00204	0.999998	8*
	Smoke	49.091	0	381.078	-0.000834	-426.014	0.5504	0.918	8

*Based on Engine 108512 regression (see page 4-7).